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# Seismic Response Analysis and Protection of Underground Monumental Structures – The Catacombs of Kom EL-Shoqafa, Alexandria, Egypt

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## 1. Introduction

Alexandria is located in eastern part of the Mediterranean Basin (Northern Egypt) and it is a place of great historical and religious interest. Numerous Catacombs and cemeteries for Greek-roman were erected in Greek-roman and Christian era has been found. They represent actually a large complex of an underground necropolis. The aim of the present study is the investigation and documentation of the existing stability conditions of the site of Catacombs in order to define the instability problems to interpret the pathology and to propose the best retrofitting procedure.

On 28 September 1900 the ground on the Hill of potsherds (Kom El- Shoqafa) spontaneously opened, and a donkey disappeared into the crevasse. The unfortunate beast had inadvertently discovered one of Alexandria's most important archaeological sites, the principal hypogeum of a funerary complex dating from the end of the first century of the Christian era and still in use at the beginning of the fourth (Empereur,2003). It had been known for some time that this area held antique tombs, since the hill has being extensively quarried to provide building materials for a fast -expanding modern Alexandria. Much had already been destroyed, though certain archaeologists of the late 19th century had been able to record other tombs that were subsequently to disappear. These reports have descriptions and drawings, which show that the complex that can visit today was part of a vast necropolis, traces of which must still exist under the foundations of the neighboring buildings.

The method of construction of these underground monuments and accesses was mainly rock cutting and carving. The Ancient Egyptian did have a large experience in cutting and digging in rocks. They used simple hand tools and with the experience they got in treatment of rock either soft (e.g. limestone and sandstone) or hard (e.g. granite, basalt, quartzite), they brought up the large number of monuments that we have discovered until now or that which may be revealed in the future. It is hard to think nowadays how they did such works with their simple tools—comparing them with the resources we have now available either mechanical, electrical or other forms of developed equipment. The tools available at that time—as already mentioned—did not exceed those made from hard stone, wood, copper, iron and bronze. We can hardly imagine that all these monuments, pyramids, temples and underground tombs were constructed by hand and by these simple tools.

The stability conditions of the historical monuments are of crucial interest, especially in regions like the Mediterranean Basin and particularly Alexandria, Egypt, where the seismotectonic and weathering regime is active and the geological structure is complex. Phenomena like settlement and slope movements as well as earthquakes and tectonic activity contribute to the damage of the historical buildings. The ground water activity is also an important factor, especially in cases underground monuments the environmental factor is also necessary to be taken in mind, when different protection measures are decided to apply (hemeda, et al, 2007).

The earthquakes affected a large variety of structural systems. The severity of damage is a function of the structural type, quality of workmanship, material, and local soil conditions. Observations of the damaged areas close to the epicenter of the Dahshour earthquake (Cairo, 1992) indicated that they can be rated VII on the Modified Mercalli intensity (MMI) scale with an estimated peak ground acceleration of about 10% g, (Badawi and Mourad, 1994).

The damages which occurred can be classified as:

- STRUCTURAL; resulting in damage to load carrying components. Foundations, Bearing walls, columns, etc.
- NON STRUCTURAL; producing damage to architectural or functional components, such as partitions, suspended ceiling parapets.

#### Structural damage

Old load bearing unreinforced Masonry walls, constructed of solid blocks, had a large number of failures and collapse. The extent of damage varied from minor cracks to complete collapse of walls.

- Failures were due to inplane cyclic shear cracking. Out-of-plane instability, and impact with adjacent buildings (pounding)
- Masonry walls that were acting as a shear walls showed flexural failures between windows, combined with some diagonal shear cracking.
- In spite of damage to wall-bearing structures, recently constructed reinforced concrete buildings did not suffer severe damage, except the complete collapse of a residential building in Cairo.

#### Non structural damage

- Different types of cracks, shear and bending were observed in partitions.
- Poorly built parapets were either dislocated or collapsed due to relative motion.
- Collapsed many masonry parapets and facades

#### Geotechnical effects of the earthquake

The soil in the area (Cairo and its districts) is silty to fine-sandy soil that makes up the valley of the Nile. When this type of soil is water-saturated and strongly shaken, it is highly susceptible to the liquefaction phenomenon.

- The soil can quickly convert from solid material into liquid which has no strength to support structures that may rest its surface on when subjected to prolonged shaking.
- The potential for widespread liquefaction is very high on the Nile flood plain, especially in irrigated fields. A highway west of the Nile sunk as much as 105m because the agricultural land adjacent to the pavement had liquefied over a few hectares

- When the strength of the soil beneath the structure vanished (due to the excess pore pressure) during the earthquake, the structures settled as the liquefied soil escaped latterly into the field.
- Also, many zones of liquefaction in the agricultural fields were reported when revealed on the ground by sand boils.

The instability problems and depreciation phenomena of subterranean monuments in Alexandria is not likely to be dominated by gravity fall or sliding on structural features, other factors such as excessively high rock stress, creep effect, poor geotechnical properties of rock structures, weathering and /or swelling rock and excessive groundwater pressure or flow, seismic loading as well as utter lack of preservation become important and can be evaluated by means of a classification of rock quality

The aim of the analysis carried out in this research is to investigate the safety margins of the underground monuments, under their present conditions, against unfavorable environmental (i.e. weathering and high underground water table), utter lack of preservation, geotechnical and extreme seismic conditions.

Underground structures safety analysis is performed using the finite element (FE) method. The research presents a comprehensive study for the underground monuments safety analysis. The safety analysis includes not only a failure analysis but the effect of weathering specially the underground water on the differential settlement will be investigated. The commercial FE package Plaxis (Karstunen et al, 2006) is used for conducting stress, as well as settlement analysis. PLAXIS is a finite element program developed for numerical analysis of geotechnical and underground structures (plaxis manual, 2002).

To compute the deformation of these underground monuments as realistically as possible, an advanced nonlinear elastoplastic material model needs to be utilized in PLAXIS which is capable of utilizing such advanced material models. Mohr's–Coulomb model is used for deformation and consolidation analysis in this study. The consolidation analysis is performed using PLAXIS utilizing Biot's consolidation theory in 2D (Biot, 1941) and the nonlinear material behavior is taken into account as mentioned before.

Also in this research, we attempt to construct and analyze a three-dimensional (3D) finite element model (FEM) of the central rotunda in catacombs of Kom El-Shoqafa with its six supporting rock piers excavated in sandy oolitic limestone deposit, using the FLAC 3D code.

For the seismic analysis, we have modeled the complex catacomb assuming an equivalent plane strain model and applying the Plaxis b.v. 8 with different seismic scenarios, corresponding to the seismotectonic features of Alexandria. Advanced soil-rock elastoplastic modeling has been used. Extensive time domain parametric analysis were performed in order to examine the response of the catacombs subjected to seismic motions with different amplitudes of ground motion and different frequency content. (Kalamata in Greece, 1986, Erzincan in Turkey, 1992, Aqaba in Egypt, 1995). The analysis takes into account the complex behavior of the structure with the aim to determine the threshold peak ground acceleration (PGA) and the corresponding developed stresses, which should remain lower than the actual strength of different elements composing the catacombs.

## 2. The objectives of this study

The Catacombs in Alexandria, Egypt from the Greek-Roman era represent cultural heritage of outstanding universal values. They suffer weathering – aging as well as multiple

geotechnical and earthquake problems. A pilot study has been carried out for on the Catacombs of Kom El-Shoqafa in order (a) to define the pathology and the causes (b) to investigates the safety assessment of the structure under static and seismic loads. (c) To assess the global risk due to several factors and (d) to define the appropriate retrofitting



Fig. 1. Plan view and the two main cross- sections of Catacombs of Kom El-Shoqafa. (a) cross-sections and (b) plan view.



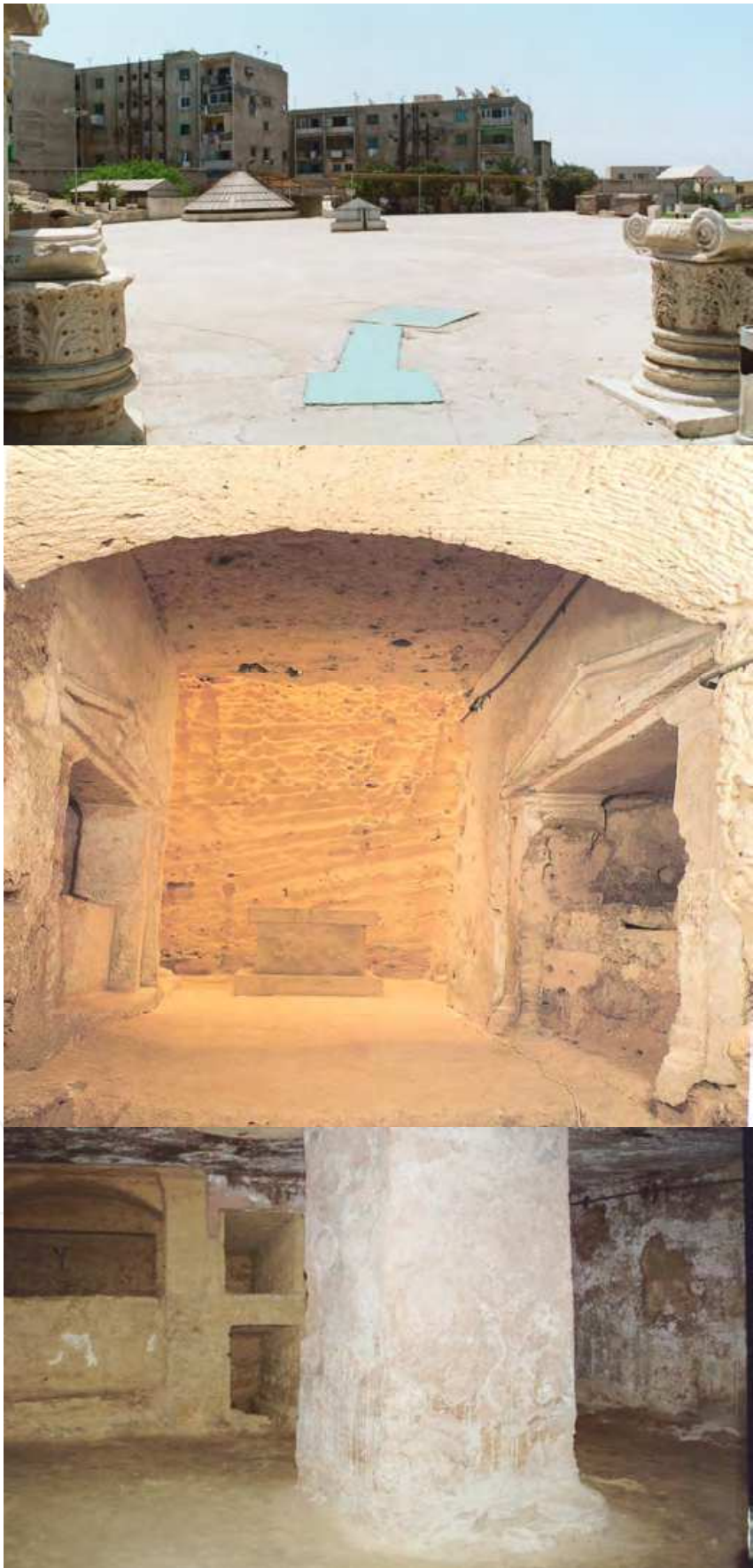




Fig. 2. Present state of the catacombs of Kom El-Shoqafa..

techniques to be applied. In the paper a general outline of the various tests, surveys and analyses is presented, highlighting the most important issues related to the static and seismic stability of underground structures like Catacombs in particularly unfavorable geotechnical and environmental conditions.

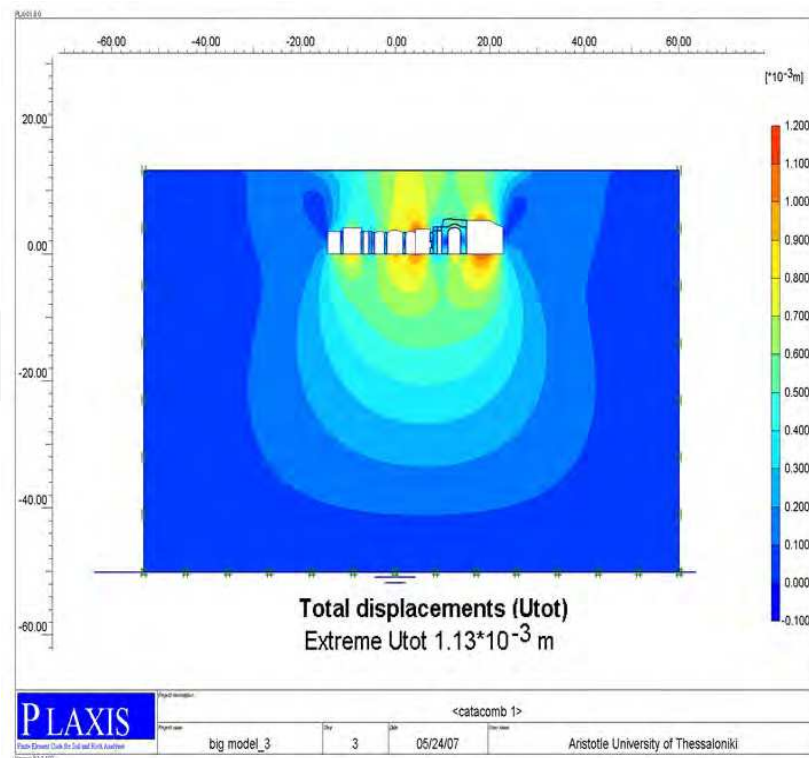
Parameters	Symbol and unit	Rock material	Brick (old restoration)
Rock unit weight	$\gamma_{\text{unsat}}$ kN/m <sup>3</sup>	18	17
Rock unit weight	$\gamma_{\text{sat}}$ kN/m <sup>3</sup>	22	20
Young's modulus	$E_{\text{ref}}$ kN/m <sup>2</sup>	2.270 x10 <sup>6</sup>	1.350 x10 <sup>6</sup>
Shear modulus	$G_{\text{ref}}$ kN/m <sup>2</sup>	8.867 x10 <sup>5</sup>	5.400 x10 <sup>5</sup>
Oedometer modulus	$E_{\text{oed}}$ kN/m <sup>2</sup>	2.902 x10 <sup>6</sup>	1.620 x10 <sup>6</sup>
Poisson's ratio	$\nu_{(\text{nu})}$	0.28	0.25
Cohesion	$c_{\text{ref}}$ kN/m <sup>2</sup>	500	450
Friction angle	$\phi^{\circ}$	35	31
Shear velocity	$V_s$ m/s	715	557.9
Longitudinal wave velocity	$V_p$ m/s	1293	9663
Uniaxial compressive strength	UCS kN/m <sup>2</sup>	2400	1100
Bending strength	$\sigma_y$ kN/m <sup>2</sup>	560	200
Shear strength	$T_f$ kN/m <sup>2</sup>	364	-
Dilatancy	$\Psi$ (o)	1 <sup>o</sup>	0

Table 1. Material properties of rock and other construction materials used for the stability analysis of the Catacombs of Kom El-Shoqafa.

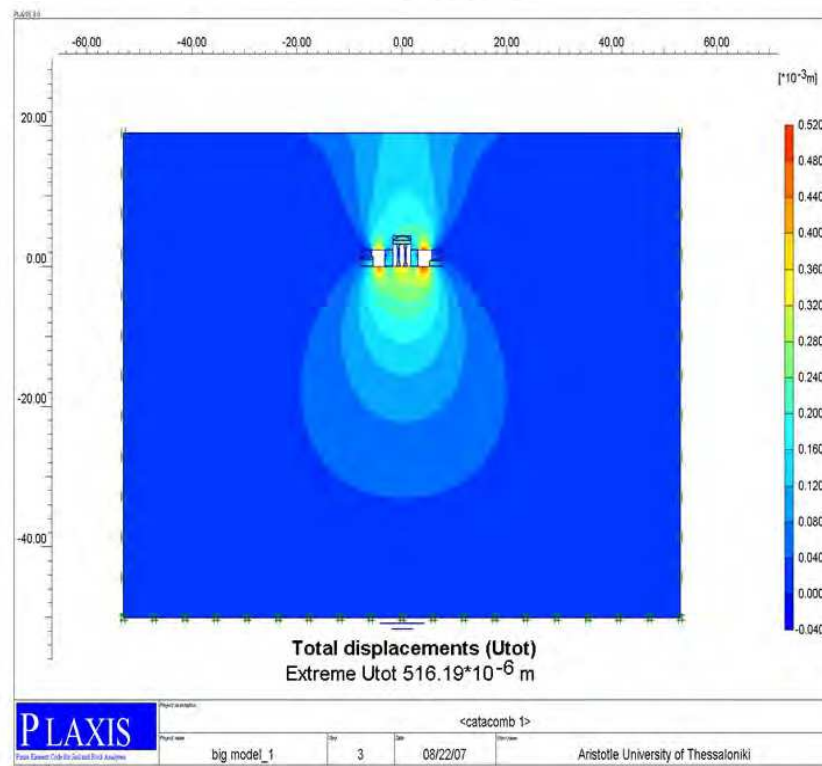
3. Preliminary 2D static analysis

In the initial static analysis, the excavation is modeled by assuming non-linear soil / rock behavior and the Mohr coulomb failure criterion. The following parameters are used:  $\phi=36^{\circ}$ ,  $c=500$  kN/m<sup>2</sup>,  $E=2.270E+06$  KN/m<sup>2</sup>,  $\nu=0.28$ ,  $V_s=715$  m/sec for the rock material, and  $\phi=31^{\circ}$ ,  $c=500$  kN/m<sup>2</sup>,  $E=1.350E+06$  KN/m<sup>2</sup>,  $\nu=0.25$ ,  $V_s=550$  m/sec for the modern brick support walls and piers. Figure 3 presents the total displacements of the soft rock excavations of catacombs of Kom El-Shoqafa, for two typical cross sections, 1 and 2, for the first and second floor, respectively. The results from the preliminary static analysis indicate that the ground displacements were small (of the order of a few millimetres; 1.13 mm); some rock pillars are under relatively high compression stresses. The calculated effective peak principal compressive stresses on supporting rock pillar 1 is about 1.42 MPa.





*First floor*



*Second floor*

Fig. 3. Total vertical static displacements at the catacombs of Kom El-Shoqafa for the first and second floor.

4. Preliminary 3D static analysis

An attempt has been made to construct a three-dimensional (3D) numerical model for the central Rotunda in the catacombs of Kom EL-Shoqafa with its six supporting rock pillars excavated in sandy oolitic limestone deposit. The objective of the 3D analyses is to evaluate the stress state in the pillars taking into account the 3D geometry. The 3D effects issue is considered on a basic engineering approach in the subsequent sections. The various simulations described herein are conducted using the FLAC 3D code (Itasca, 2007).

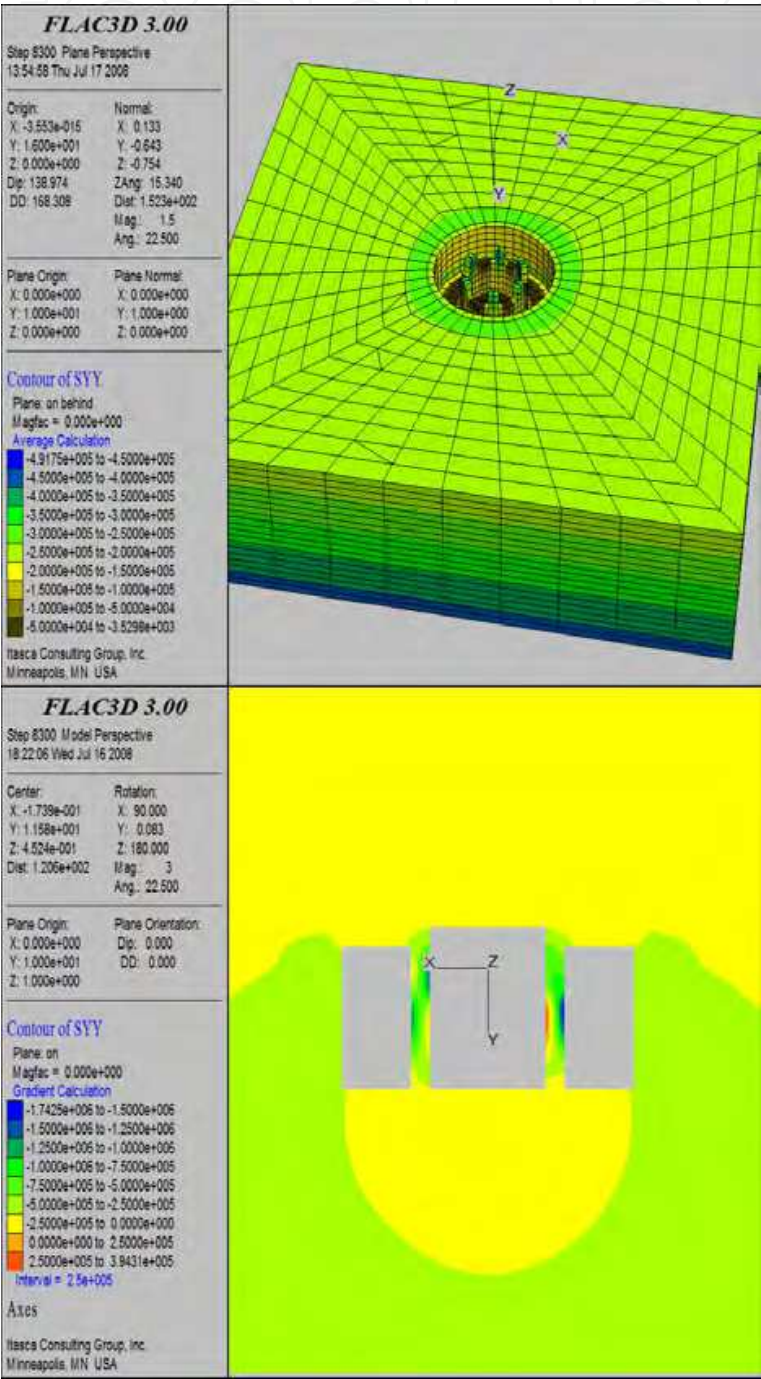


Fig. 4. Contour lines of vertical effective stresses  $\sigma_{yy}$  through the rotunda. The maximum effective compressive stresses on pillar\_1 =  $-1.74 \times 10^3$  (×) kN/m<sup>2</sup>.

The results from the 3D static analysis indicate that the ground displacements above the rotunda (catacombs) small. The maximum total (vertical) displacements range between 2.6 mm and 3 mm in the whole domain. The peak horizontal displacement is about 1.0 mm. Some rock piers are under relatively high compression stresses. The calculated peak effective principal vertical compressive stresses on supporting rock pillar 1 is  $1.74 \times 10^3$  KN/m<sup>2</sup> and the calculated peak effective principal tensile stress is about 200 KN/m<sup>2</sup>. The factor of safety of the rock pillar 1 is 1.47, (note that the acceptable safety factor for the underground structures is > 1.6 in static state ). Also the overstress state is beyond the elastic regime (limit of domain) (Hemeda, 2008).

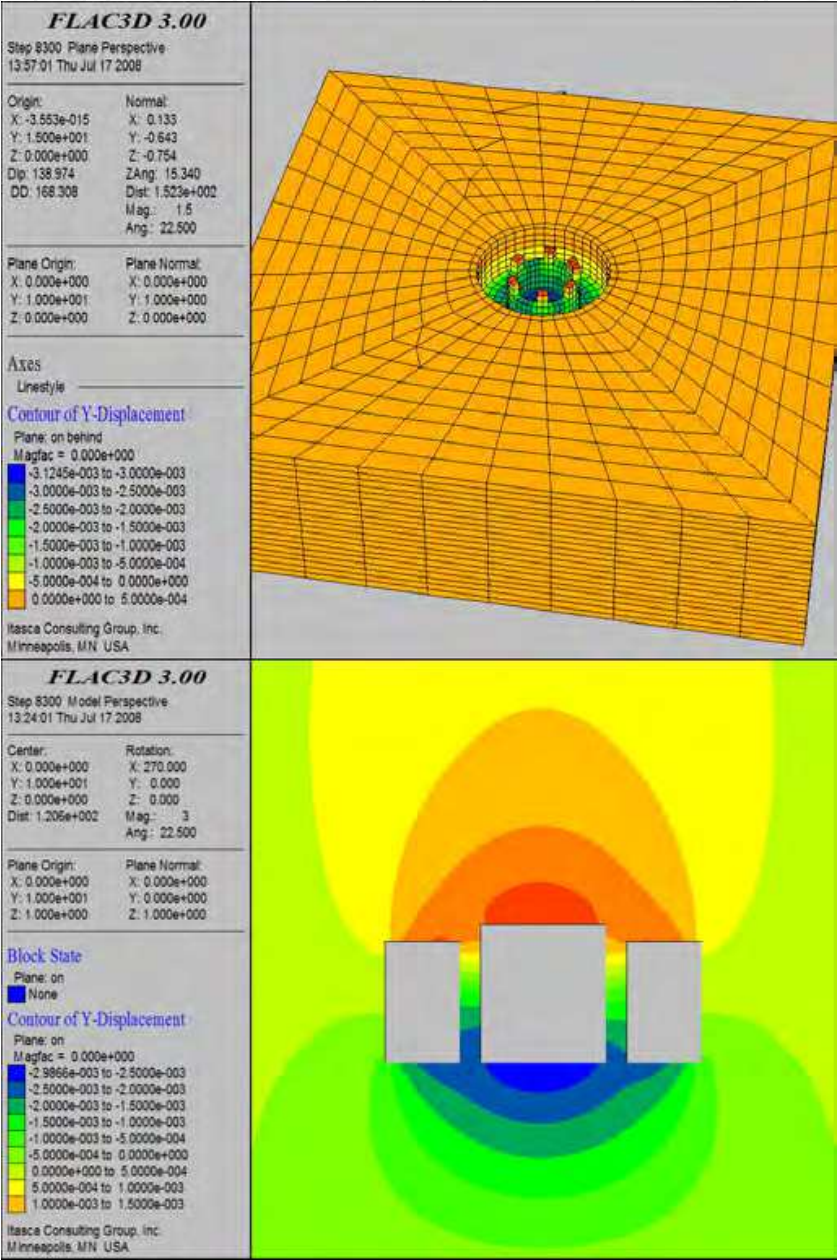


Fig. 5. Results from the 3D analysis indicating that the maximum ground displacements above the rotunda are relatively small (of the order of 2.6 mm), and the maximum horizontal displacement is about 1 mm.



## 5. Seismic response analysis

In the present study, we have selected three reference earthquakes to be used as input motions to the time-history analysis of the monumental structure studied, namely: (i) Aqaba, Egypt, 1995, (ii) Erzincan, Turkey, 1992 and (iii) Kalamata, Greece, 1986. The time histories (Figure 6) of these earthquakes representing different seismotectonic settings and frequency content, were scaled to three peak ground acceleration values equal to 0.08g, 0.16g, and 0.24g (g is acceleration due to gravity), respectively. The design acceleration in Alexandria according to the Egypt seismic code is 0.08g (ECP-203). The structures have been analyzed under single horizontal ground acceleration and not under the three ground acceleration.

### 5.1 Seismicity of Egypt

Egypt lies at the north east of the African tectonic plate whose borders are the Red Sea and the Jordan Valley. Another major tectonic feature is the African Rift Valley which extends from the Red Sea down through Ethiopia towards South and East Africa. The contemporary geological setting of the region is mainly governed by active extensional tectonics taking place within the Gulf of Suez Rift. For over 20 years, geologically young faulting has been known to exist both along the margins and within the Gulf of Suez (Said, 1990).

In the 15th century, an Egyptian scholar listed more than 30 earthquake events that happened from AD 796 to 1500. The Dahshour earthquake was the latest in a long history of earthquakes that occasionally cause damage to buildings in Cairo and surrounding areas in northeastern Egypt. On 7 August 1847, an earthquake with an estimated magnitude of 6.8 occurred about 100 km southwest of Cairo, near El-Fayoum. Three thousand houses and 42 mosques were destroyed in El-Fayoum and damage was extensive in Cairo (Kebeasy et al., 1976).

Two recent earthquakes occurred within the last three decades. The first, having a magnitude 7.0, occurred in the northern part of the Red Sea on 31 March 1969. It caused landslides, rock falls, and fissures, in addition to damage to a power station and some hotels in a city nearby (Maamoun et al., 1984). The second earthquake occurred on 14 November 1981, in Aswan, 1000 km south of Cairo, along the Nile River. It measured 5.6 on the Richter scale, in an area that was considered a seismic. Some scientists attribute this earthquake to the construction of a dam along the river, resulting in an artificial reservoir, approximately 300 km long, and having a maximum capacity of 164000 million cubic meters (Bolt, 1988).

### 5.2 Seismicity of Alexandria

Alexandria during his long history has suffered important seismic damages from near and distant sources earthquakes. As the under-water archeological remains in Abou Kir bay strongly support, either local or remote earthquakes (El-Sayed, 2004) destroyed the city. Seismogenic zones such as the Red Sea, Gulf of Aqaba-Dead Sea Hellenic Arc, Suez-Cairo-Alexandria, Eastern-Mediterranean-Cairo-Faiyoum and the Egyptian coastal area may all affect the city. However, the seismic hazard of the city has not been fully defined.

Alexandria is located approximately 300 to 600 km from three known active plate boundaries, namely: the Red-Sea, the Gulf of Aqaba and the Hellenic Arc (Mckenzie 1970, 1972; Sestini, 1984; Mesherf, 1990). The interaction among these three plate boundaries created major fault zones in Egypt as: (1) Eastern- Mediterranean Cairo Faiyoum fault zone (Neev, 1975; Sestini, 1984; Mesherf, 1990), (2) Suez-Cairo-Alexandria fault zone (Kebeasy,



1990). These fault zones are very close to the city of Alexandria. Moreover, deep seismic sounding reveals that there are minor faults such as Rosetta fault which trend a few kilometers from Alexandria city (Hussein & Abd Allah, 2001).

Because of this complex tectonic setting, many earthquakes occurred approximately Alexandria, both in recent and historical time (Ambraseys et al., 1994; Maamoun et al., 1984). The spatial distribution of the earthquakes epicenters shows that there are areas of very intense (e.g., plate boundaries) and others of low (e.g., offshore area) activities. For those of intense seismicity, there are a considerable number of focal mechanisms that allow us to understand its geodynamic behaviors (Mckenzie, 1970; and Rotstein and Kafka, 1982; Sestini, 1984; CMT database). Controversy, the number and quality of the focal mechanisms available for those of low seismic activity (like the Egyptian coastal zone) are not enough to have the clear understanding for the tectonic setting (Sestini, 1984; Kebeasy, 1990; Mesherf 1990).

Because of this complex stress regime, damaging earthquakes had occurred in the vicinity of Alexandria (Ambraseys et al., 1998; Kebeasy, 1990; Maamoun et al., 1984). Some of these damaging earthquakes are apparently missing. As an example, the damage in Menouthis and Herakleion is more likely caused by an earthquake (which is not known yet). This is supported by: (1) the collapsed columns are falling down in the same direction NE-SW, (2) the presence of coins and jewelry suggest a sudden collapse, (3) the sharp sand grains in the bottom of Abou kir Bay reflecting active tectonic environment, and (4) the Cairo- Alexandria fault system (NE-SW) is passing by the area and recently generated frequent moderate earthquakes (GEOTIMES, 2000). This does not exclude the possibilities of land subsidence as suggested in the STANFORD REPORT (2000).

### 5.3 Seismic input

In the present study, we have selected three reference earthquakes. (i) Aqaba, Egypt, 1995 (ii) Erzincan, Turkey, 1992 and (iii) Kalamata, Greece, 1986. The time histories (Figure.6) of these earthquakes representing different seismotectonic settings and frequency content were scaled to three peak ground acceleration values equal to 0.08g, 0.16g, and 0.24g respectively. And they are used as input motions at the bedrock. The design acceleration in Alexandria according to the Egypt code is 0.08g.

We believe that with the advances in computational methods it is now possible to predict with reasonable accuracy the seismic demands on these geometrically complex monuments. Specially, computer modeling and simulations are very useful tools for identifying regions of stress concentration where only non-invasive techniques are allowed. Accurate quantification of stresses are also useful for understanding the direction of cracks propagation and for quantifying the seismic demands on whatever new materials may be introduced in the retrofit program. Three earthquakes were chosen:

Aqaba: 22/11/1995, M=7.1, Ml=6.2: Station Eilat. Distance (km): Closest to fault rupture (93.8).

Erzincan: 13/3/1992, Mw=6.9, Ms=6.8. Station: 95 Erzincan, Rrup=2km, Re=1km.

Kalamata: 13/9/1986. 17:24:35, Ms=5.8 .Mw=5.9, Ml=5.5. Station: Old telecommunication building, Re=10 km.

22 November 1995, an major earthquake (Aqaba earthquake) with a magnitude of 6.2 on the local scale ML, and a moment magnitude of MW D 7:1, (PDE bulletin, 1996), struck the

shorelines cities of the Gulf of Aqaba, such as Aqaba (Jordan), Eilat (Israel), Hagel (Saudi Arabia) and Nuweiba (Egypt), Damage occurred in many parts northeastern Egypt as far as Cairo. This major event was followed by 2089 earthquakes ranging in magnitude from 2 to 5.5 on local magnitude (ML) recorded and/or analyzed by the Jordan Seismological Observatory (JSO bulletin, 1998). This seismic swarm activity began on 22 November 1995 and continues at least until the end of December 1997, (EID AL -TARAZI, 2000).

The Kalamata earthquake was recorded on hard ground at a distance of about 9 km from the epicenter and its magnitude was  $M_s=6.2$ . The record samples the near field strong motion that caused considerable damage to the buildings of the city of Kalamata. The duration of the strong motion is about 6 sec and the maximum accelerations are 0.24g in the N-S direction and 0.27g in the E-W direction. The corresponding peak velocities are 32.0 and 23.5 cm/s, respectively.

The 13 March 1992 Erzincan earthquake,  $M=6.8$ , occurred in the eastern half of the Erzincan basin. The largest aftershock took place near Pülümür on 15 March 1992. No clear surface breaks were observed, although teleseismic studies suggested that it was a strike-slip earthquake striking parallel to the North Anatolian fault, with a focus of approximately  $10\pm 2$  km depth, 30 km rupture length, 95 cm of slip, and a  $1.16\times 10^{26}$  dyn.cm seismic moment. The aftershock distribution concentrated at an area of the intersection between the North Anatolian fault and the Ovacik fault. These results indicate that the previously suggested seismic gap along the North Anatolian fault, east of Erzincan, remains unruptured (AYKUT et al 1993).

The criterion for this choice was their different frequency content, as they will give information about the response of these structures in different period ranges Figure (6) shows one of the horizontal components of acceleration for each record. The records were retrieved from PEER and ESMD online database.

In order to estimate the threshold PGA values to collapse, a set of parametric analysis was carried out. These structures were subjected to increasing level of horizontal accelerations.

Figures (7) through (13) depict the main results of the analysis. In case of the Aqaba earthquake, it is clear that a great part of seismic energy is dissipated by the upper parts of catacombs (ground surface) even for small values of PGA. Kalamata and Erzincan input motions give much lower displacements values (Arias' intensity and total duration will explain the difference in responses from the three ground accelerations). The maximum horizontal displacement at the top of catacombs for Aqaba earthquake at  $PGA = 0.24g$  earthquake scenario was  $u_x = 7.95$  cm, while the peak vertical effective principal stress was 4190 kN/m<sup>2</sup>. For the Erzincan and Kalamata earthquakes, the respective values were 3400 kN/m<sup>2</sup> and 3580 kN/m<sup>2</sup>, respectively. Moreover, the maximum horizontal displacement at the top of the catacombs was 2.34 cm and 2.01 cm for Erzincan and Kalamata earthquakes respectively. The maximum vertical displacement at the top of catacombs, are 3 mm, 2.6 mm, and 5.3 mm for Kalamata, Erzincan, and Aqaba earthquakes, respectively.

Given the value of the static strength estimated in the laboratory ( $UCS=2.5$  MPa), the seismic analysis of the catacombs complex proves that the supporting rock piers and columns, which are the most vulnerable parts of the whole complex, are rather safe for PGA values lower than 0.24g in case of the Kalamata and Erzincan earthquakes and  $PGA = 0.12g$  for the Aqaba seismic scenario (see Figure 13a, b).

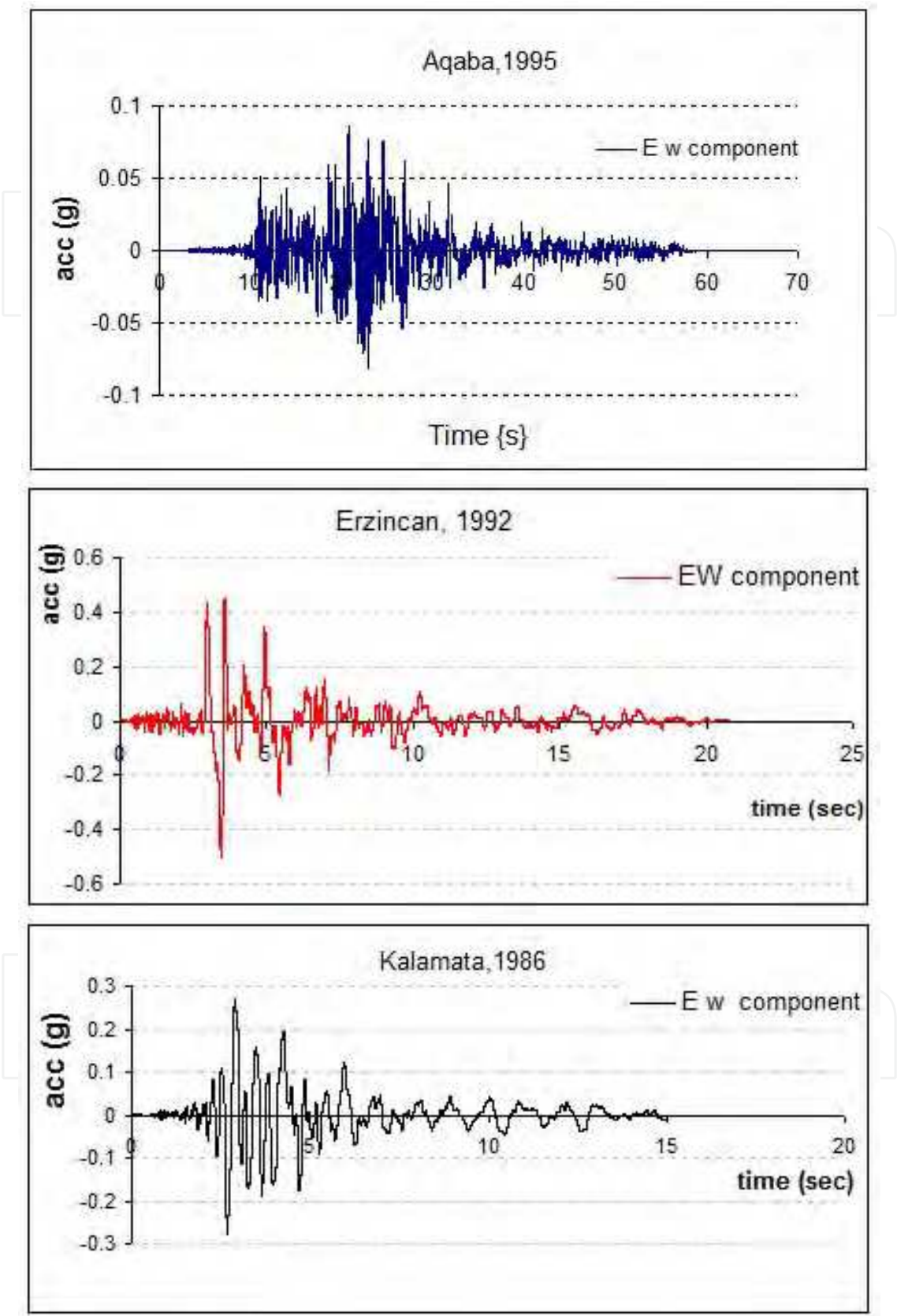
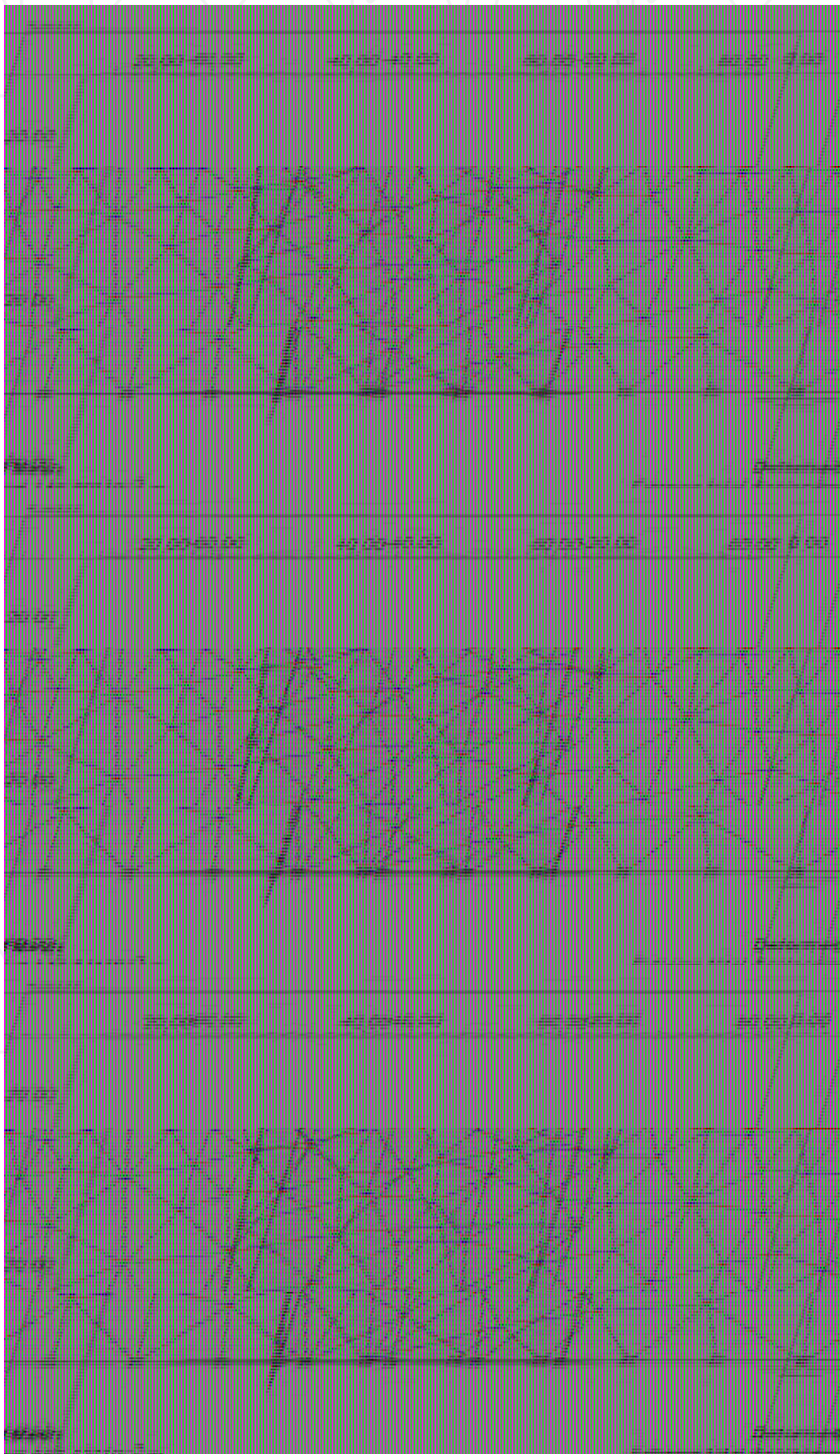


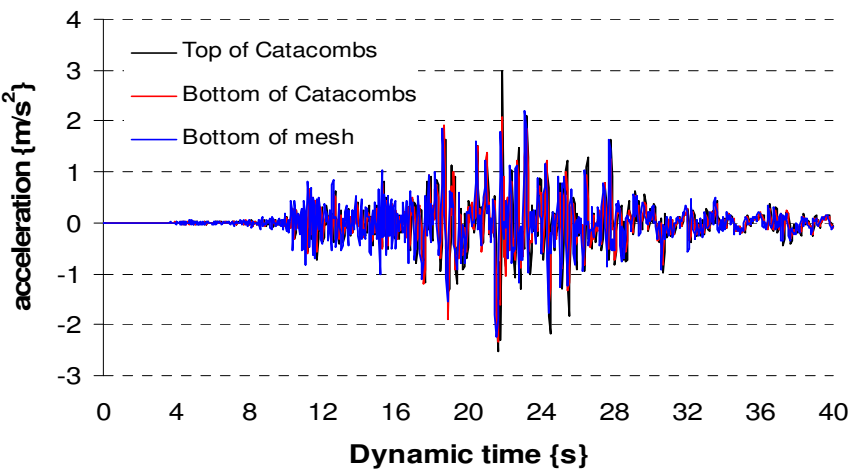
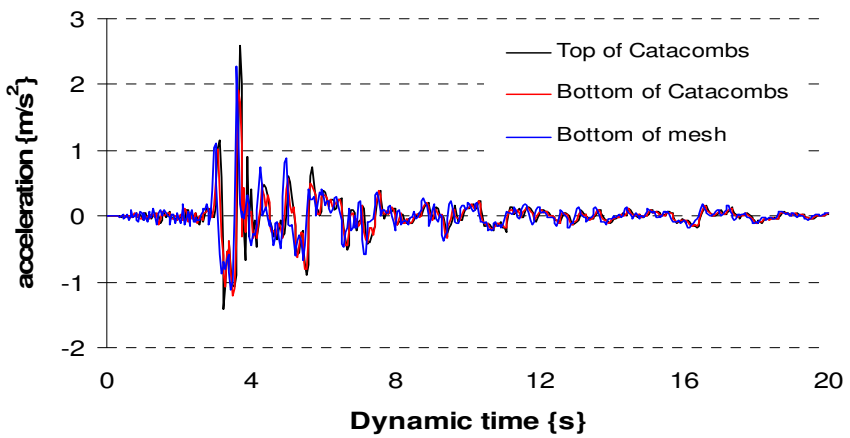
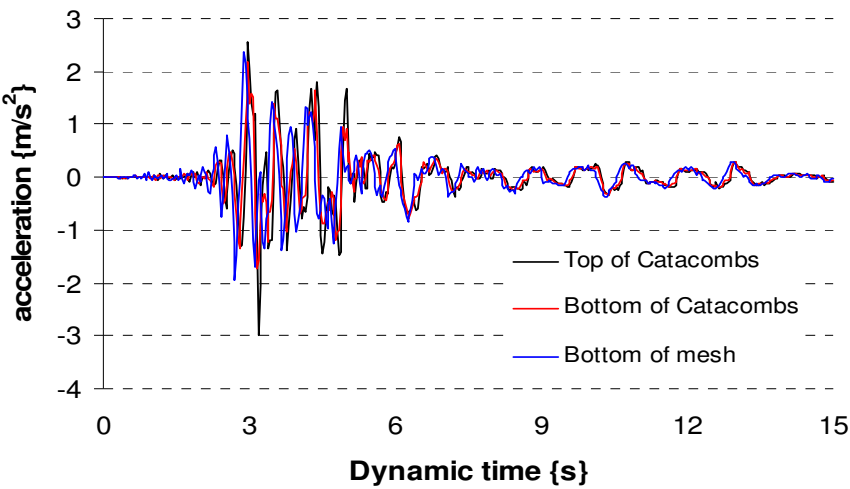
Fig. 6. Seismic excitations at the bedrock for the reference ground motions (acceleration-time history). (a) Aqaba, 1995 (b) Erzincan 1992, and (c) Kalamata, 1986 earthquakes.



For larger earthquakes, which are most likely to happen in the region, the seismic stability of the catacombs is not satisfied and it is necessary to proceed to specific retrofitting works to upgrade their seismic performance. The maximum relative horizontal displacements of the top and the base of the rock piers are of the order of 3 to 5 mm (Figure 10). Considering that the induced seismic ground deformations are better correlated with the intensity of damages in underground structures, the seismic design of the catacombs must be based on these kinematic forces.







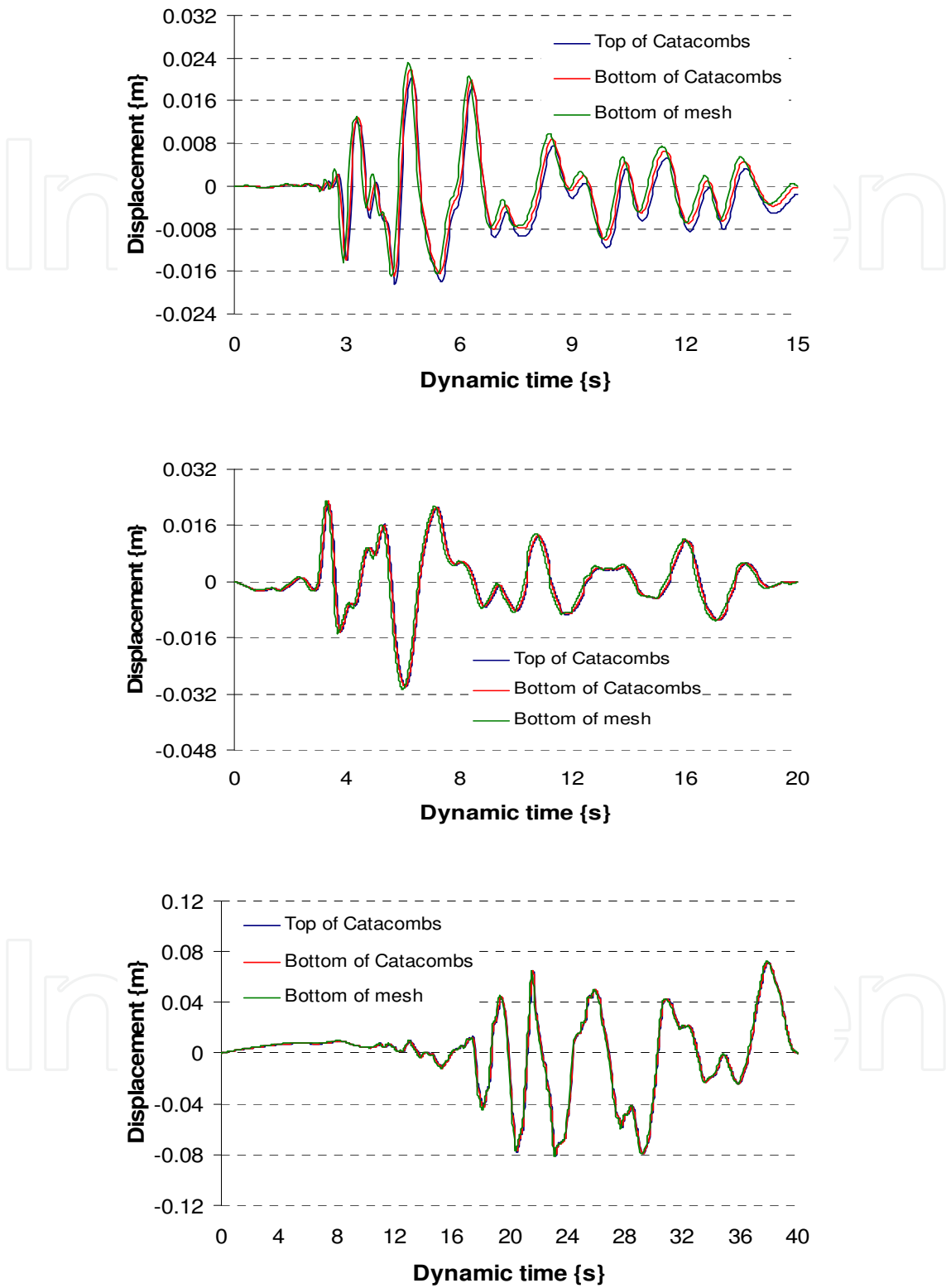
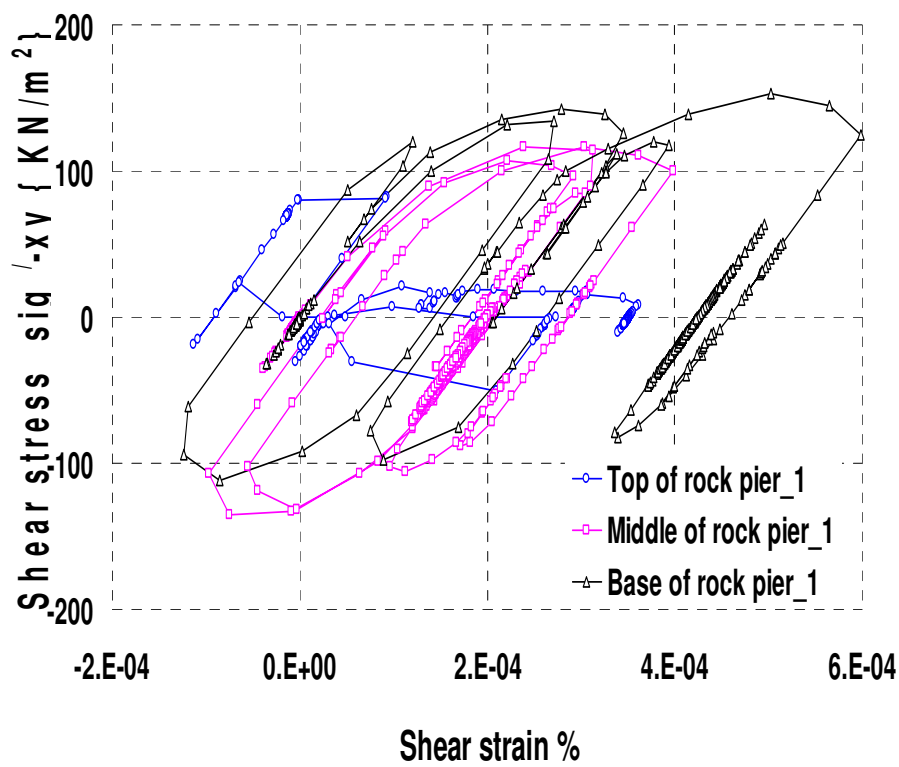
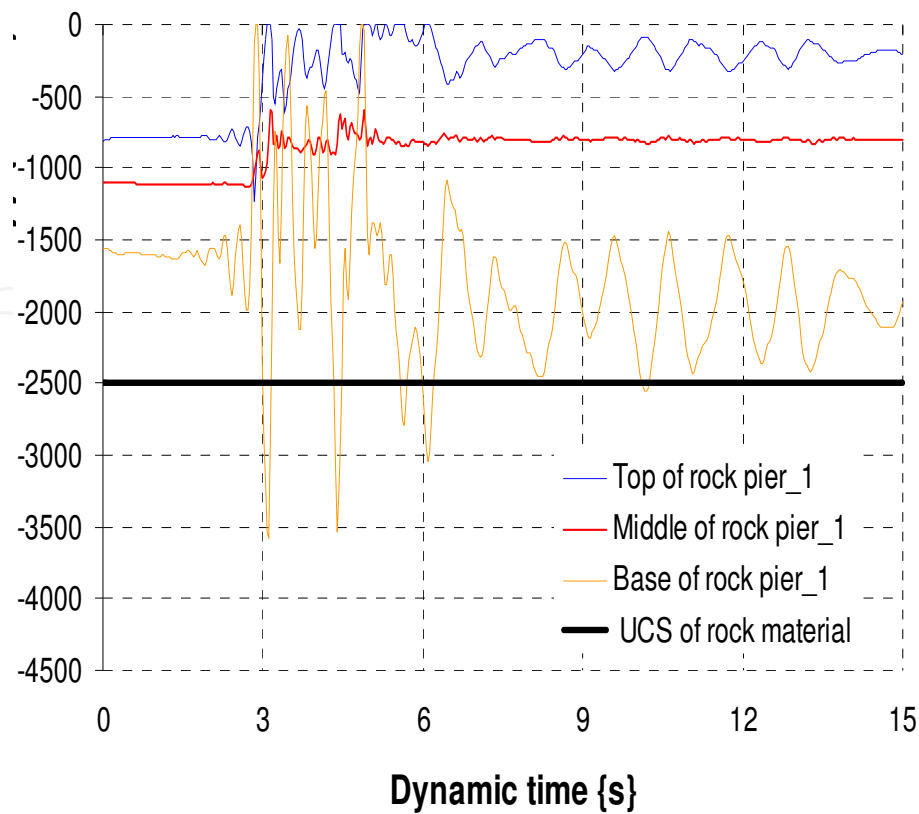
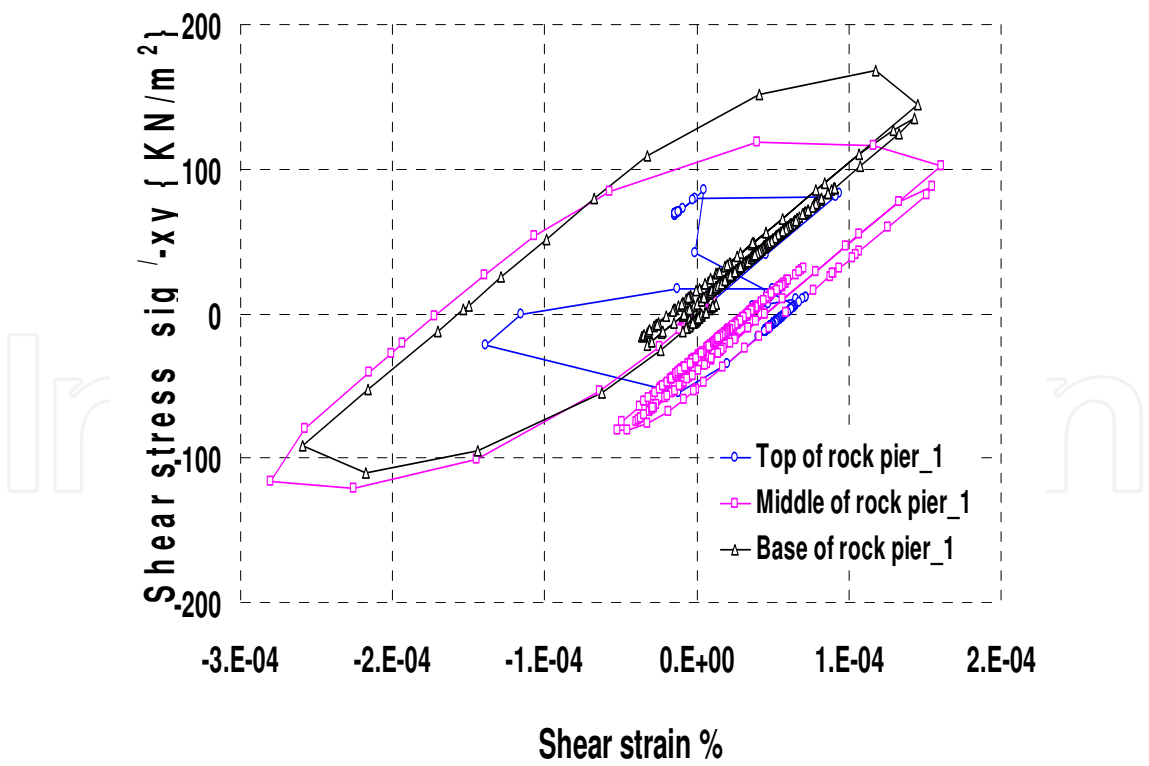
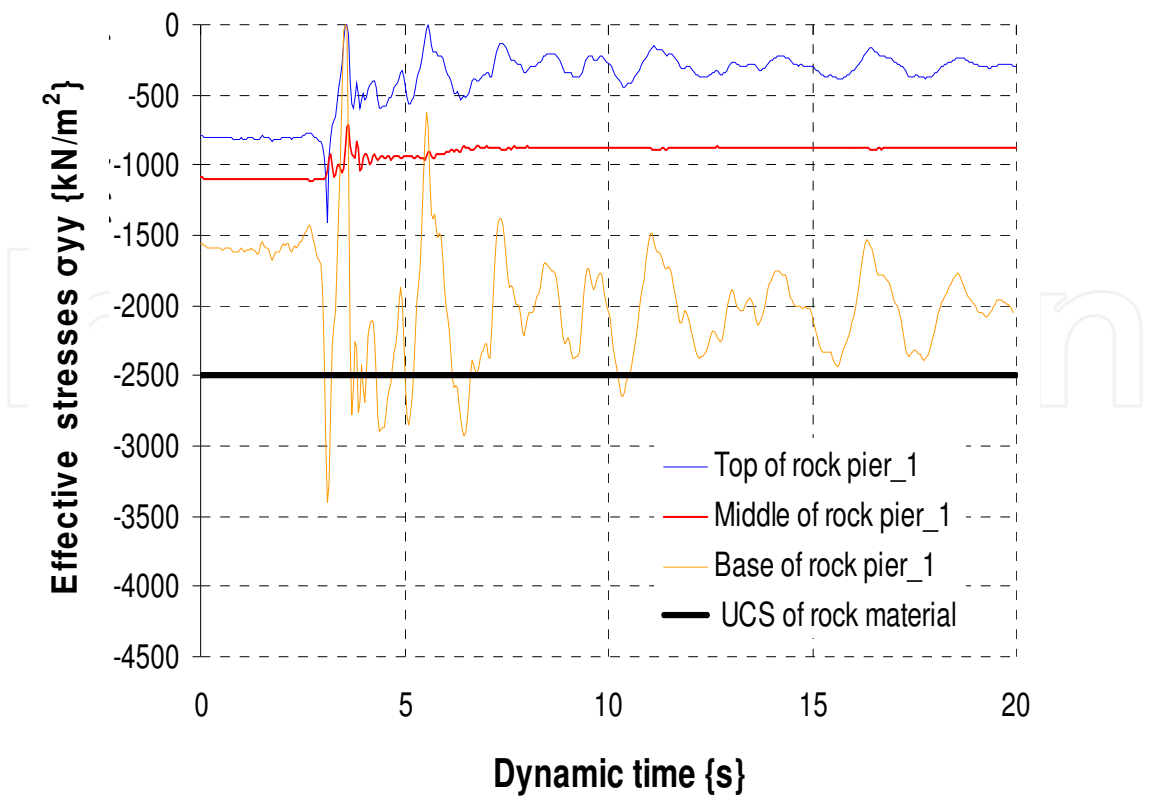


Fig. 7. Deformed meshes and peak total displacement, and acceleration, horizontal displacements-time histories, (a) Kalamata , (b) Erzincan , and (c) Aqaba eartquakes. Input motion PGA = 0.24g. Catacombs of Kom El-Shoqafa, a typical cross section 1, first floor.

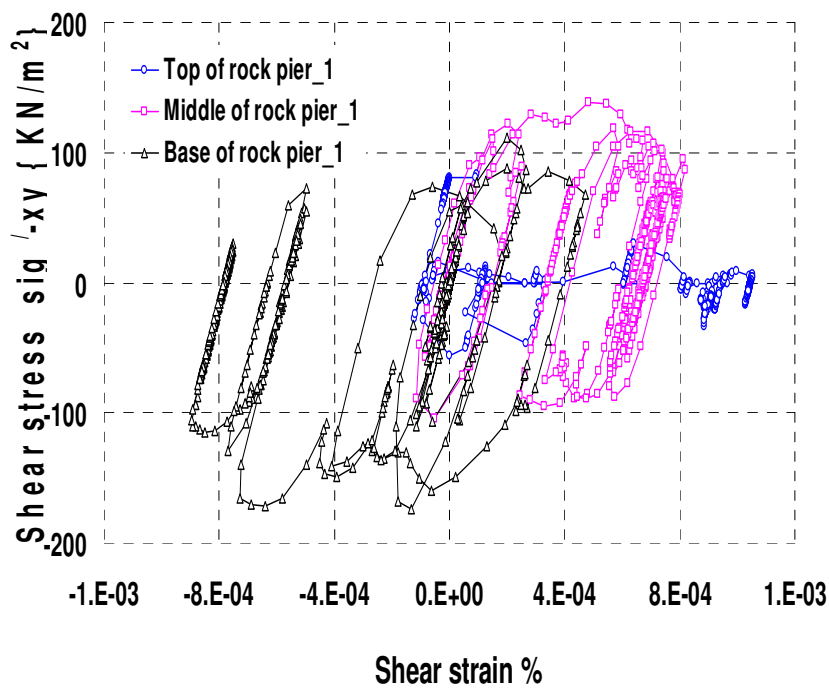
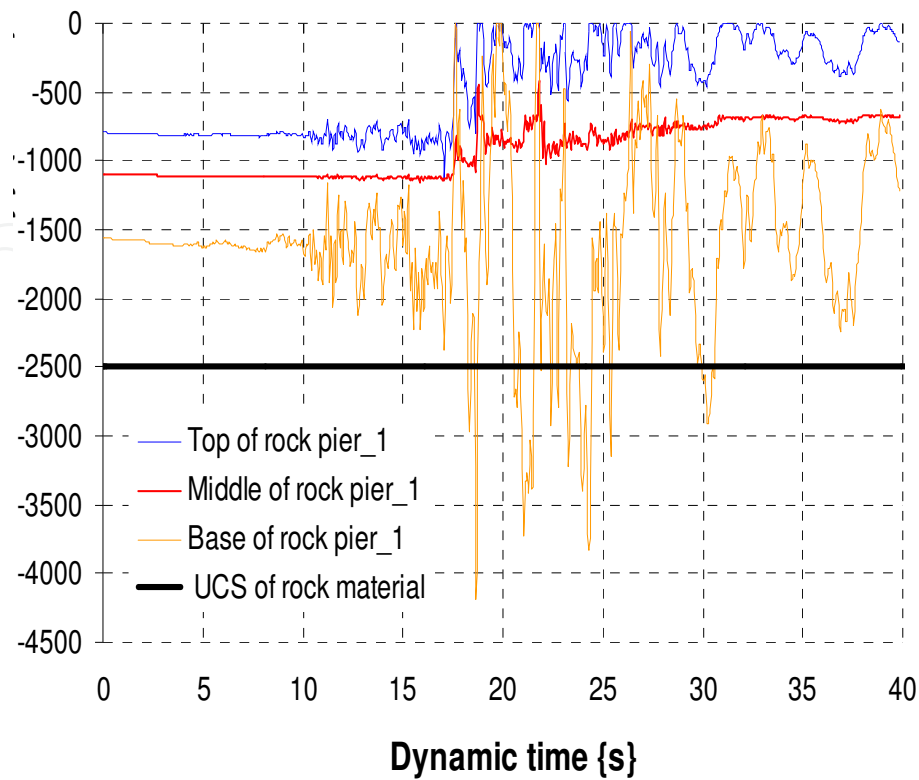


a)



b)





c)

Fig. 8. Effective vertical compressive stresses  $\sigma_{yy}$  - time histories and shear stress versus shear strain for the most critical rock pier 1 (Figure 9 at the right side of rotunda). (a) Kalamata (b) Erzincan (c) Aqaba earthquakes. PGA value = 0.24g.

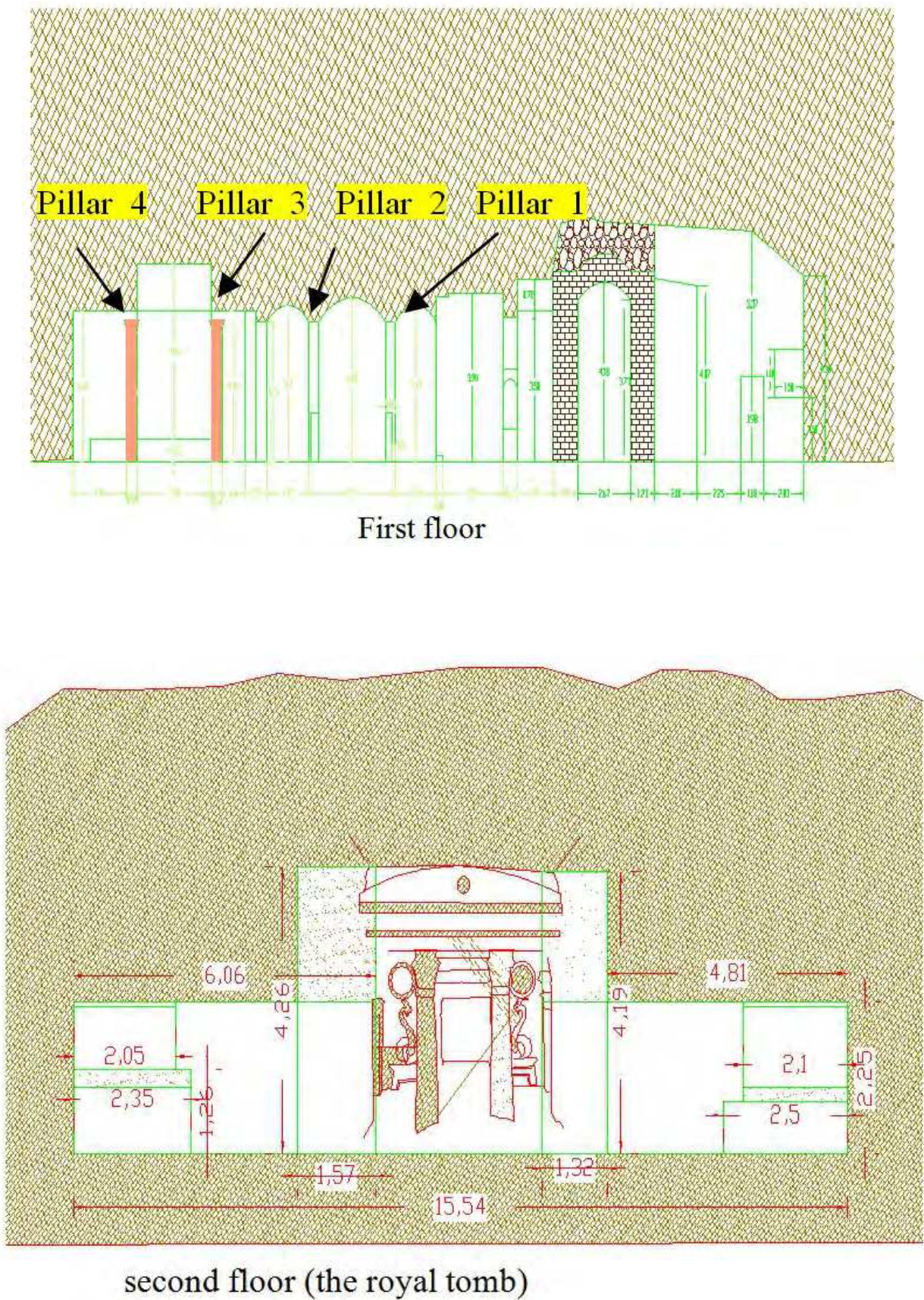
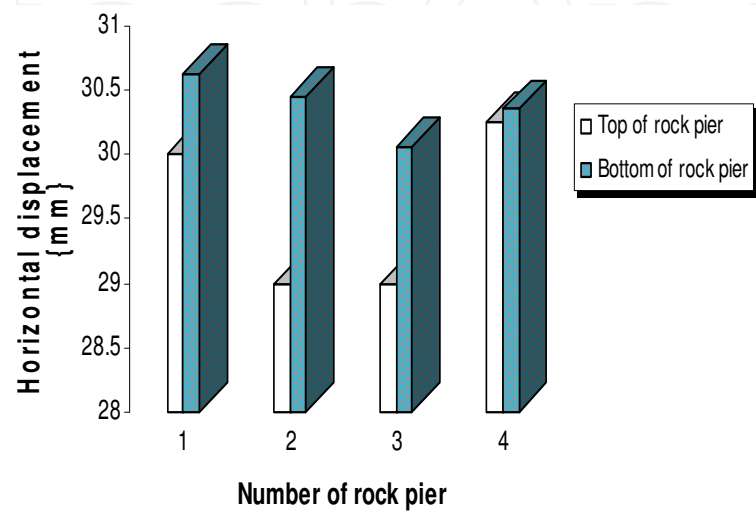
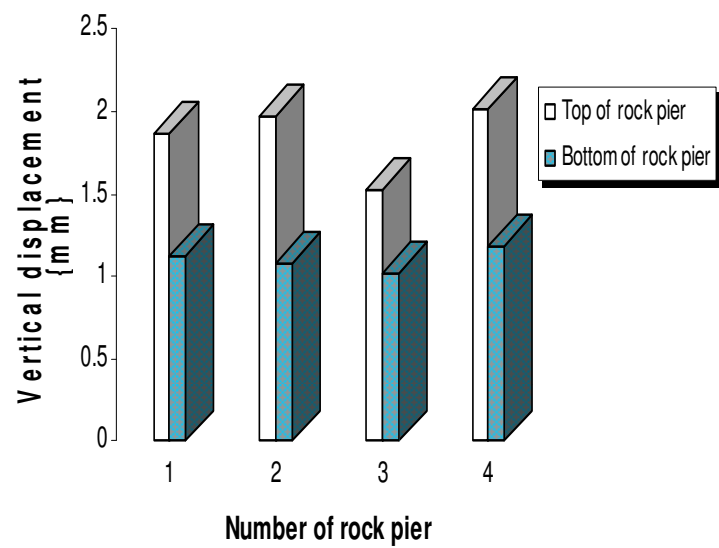
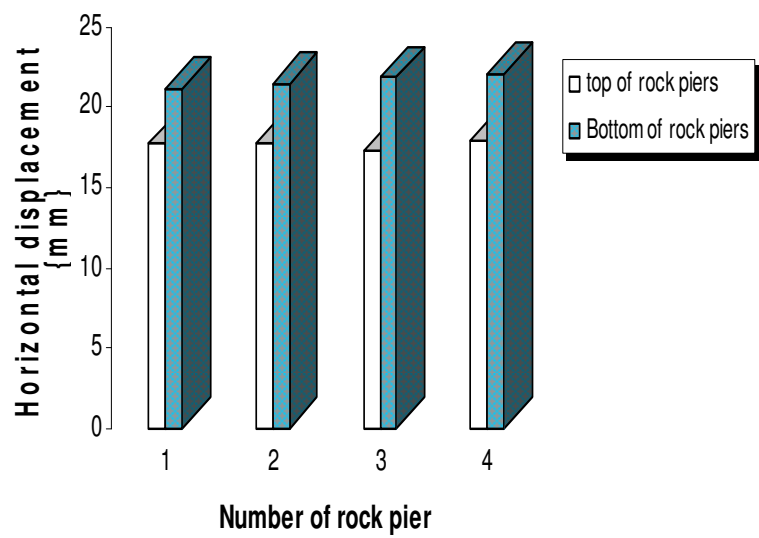


Fig. 9. The typical cross sections 1 and 2, which have been used in the seismic analysis.





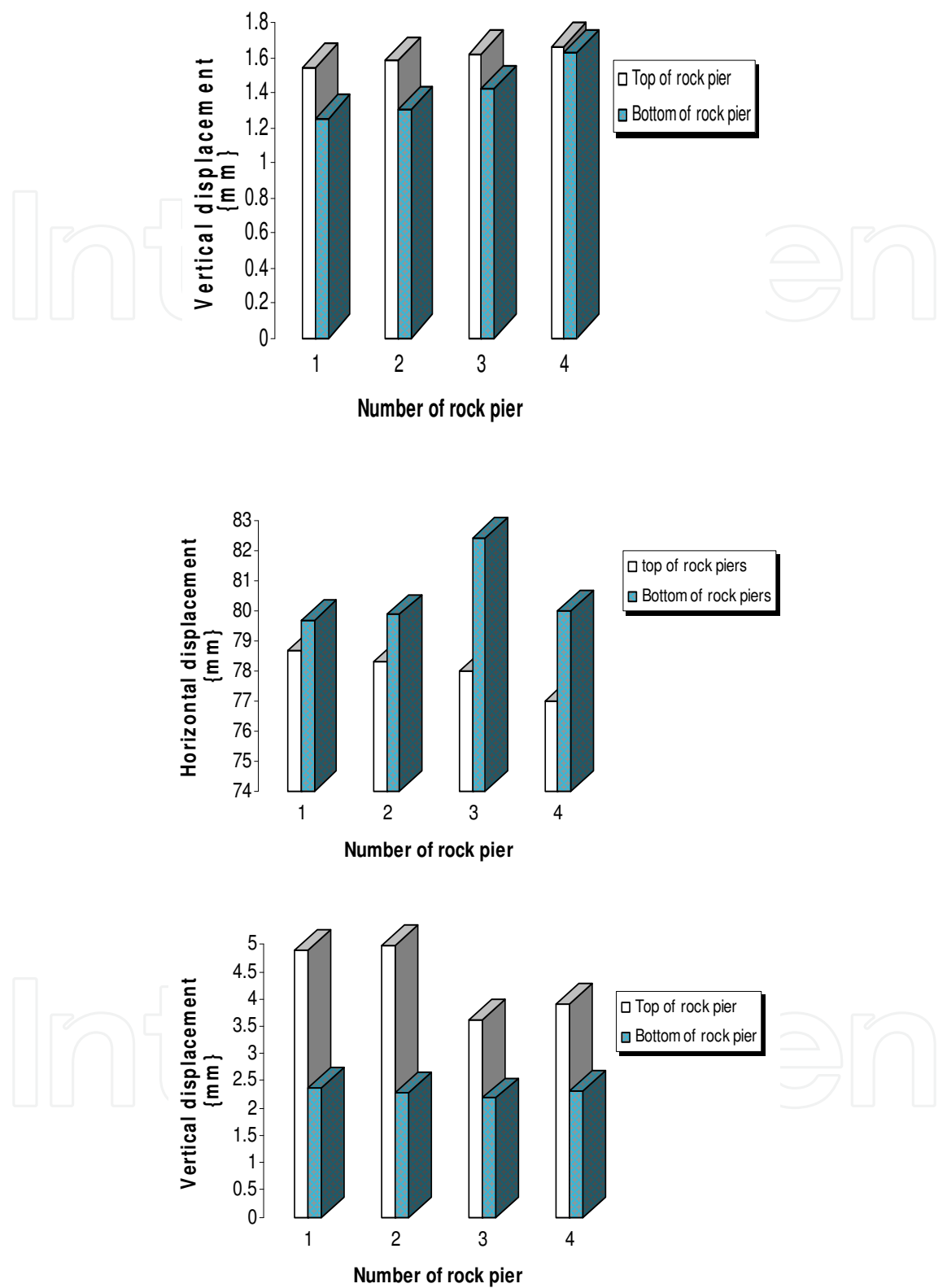
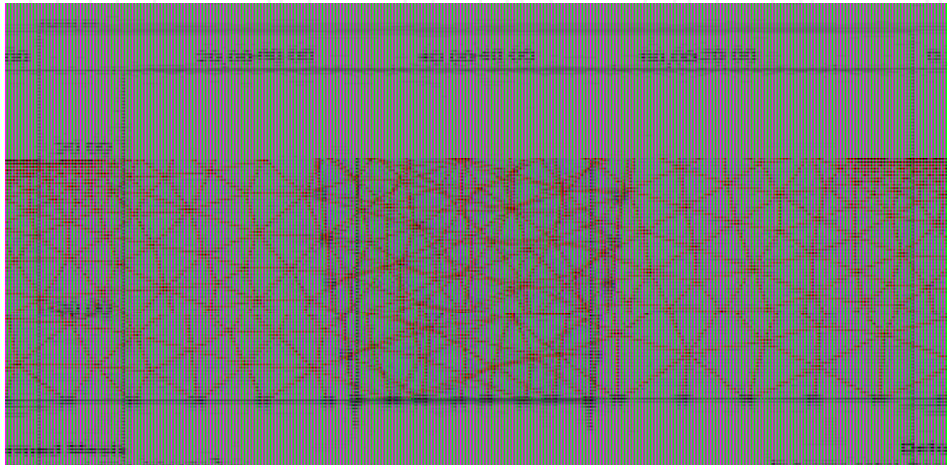
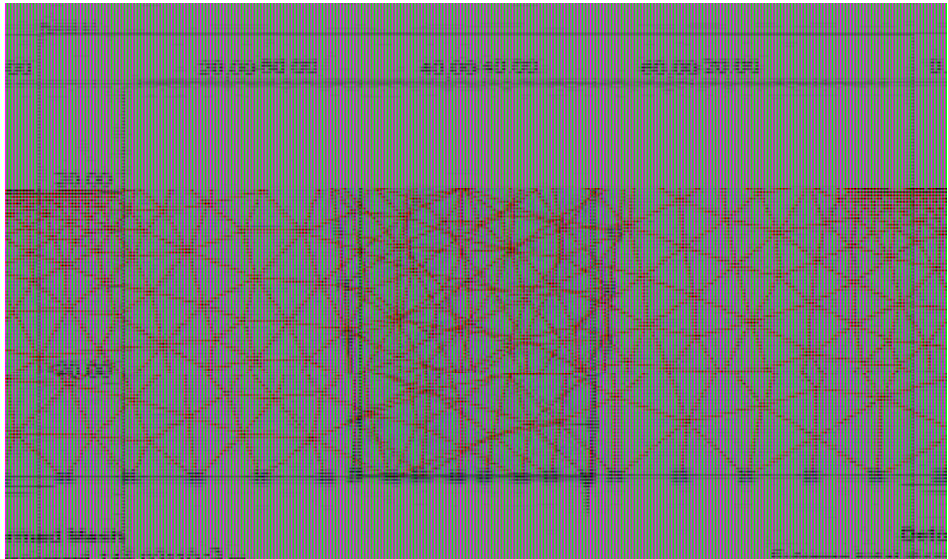
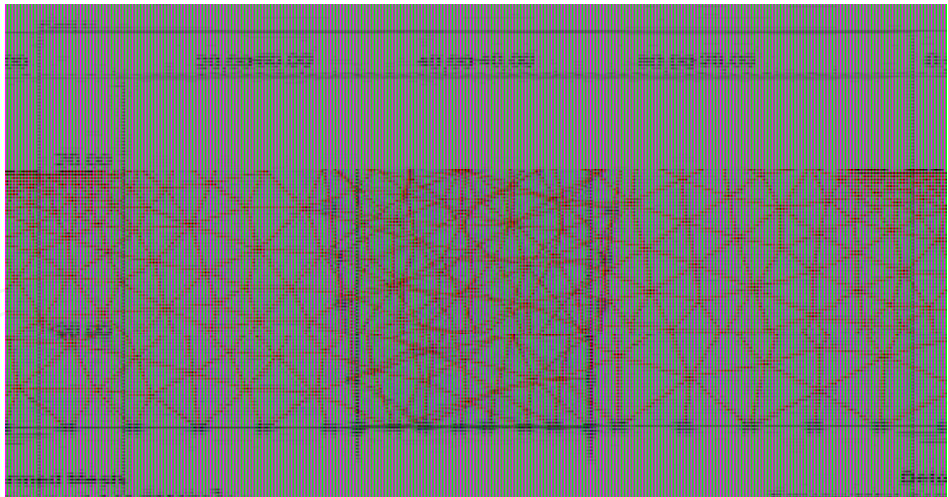
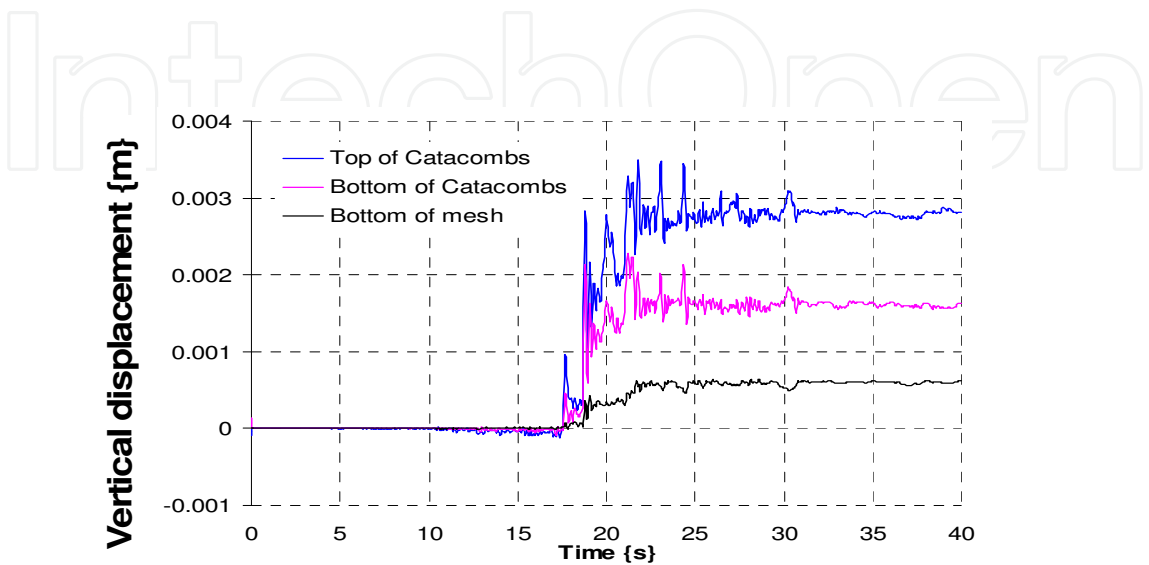
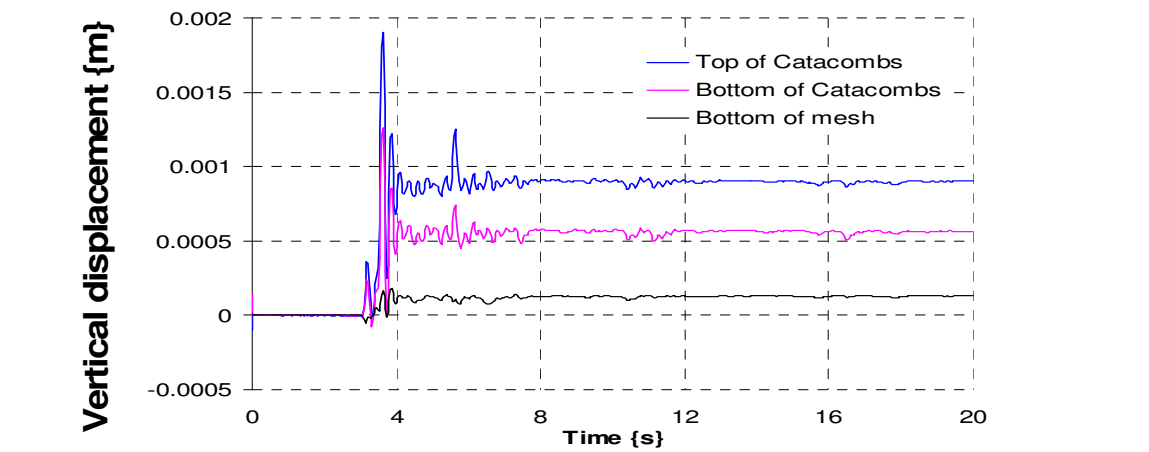
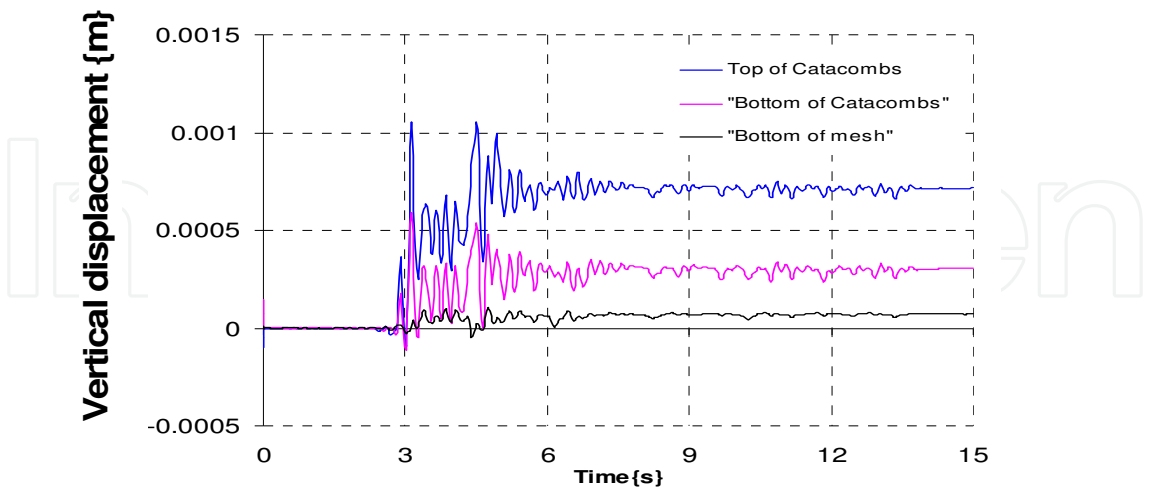


Fig. 10. Differential horizontal and vertical displacements on the top and base of the rock piers in the catacomb complex (a) Kalamata at time (t) =4.60 sec, (b) Erzincan at (t) = 7.09 sec, (c) Aqaba at time (t) = 23.22 sec. PGA = 0.24g.







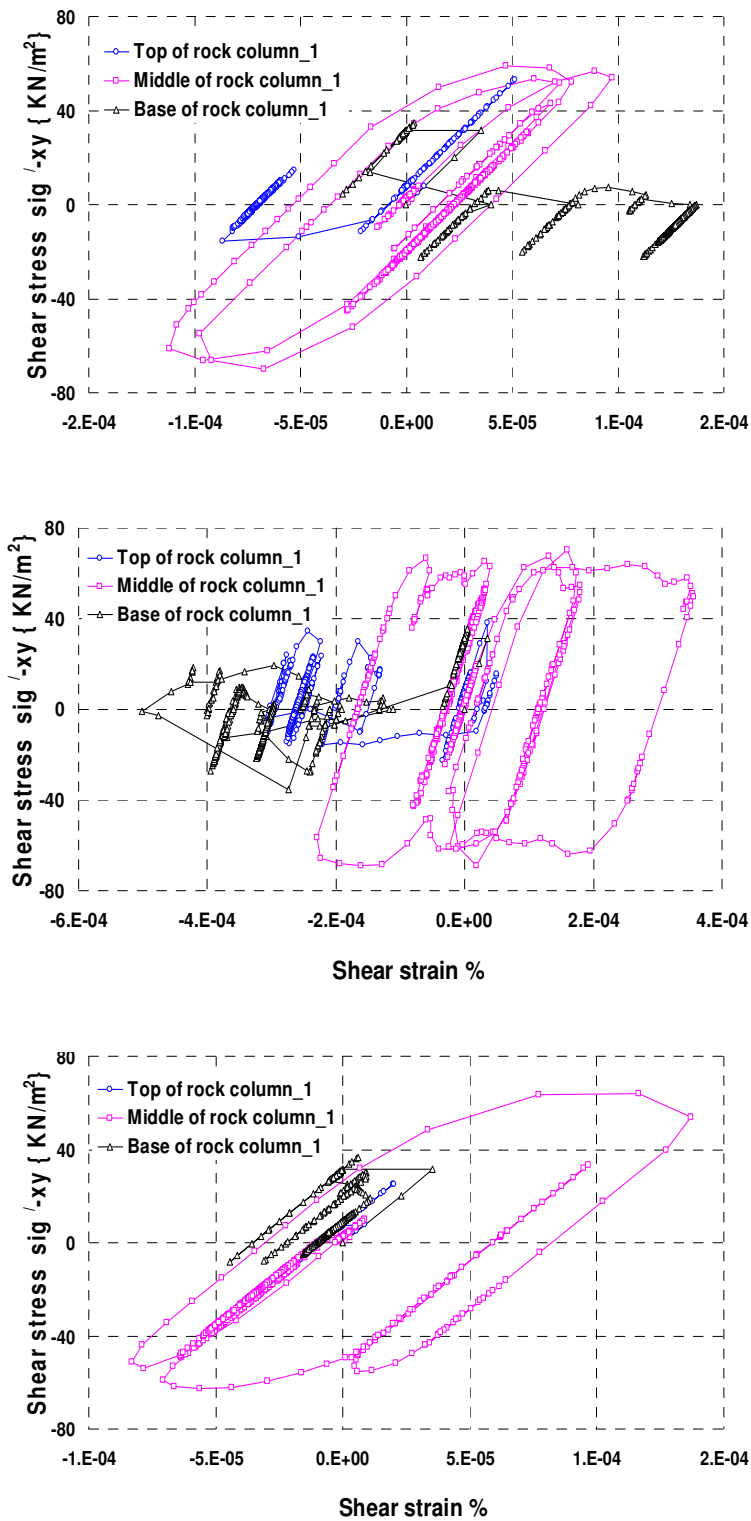


Fig. 11. Deformed meshes, vertical displacement-time history, shear stresses-shear strain, (a) Kalamata , (b) Erzincan , and (c) Aqaba earthquakes. Input motion PGA = 0.24g. Catacombs of Kom El-Shoqafa, a typical cross section 2, second floor, the royal tomb.

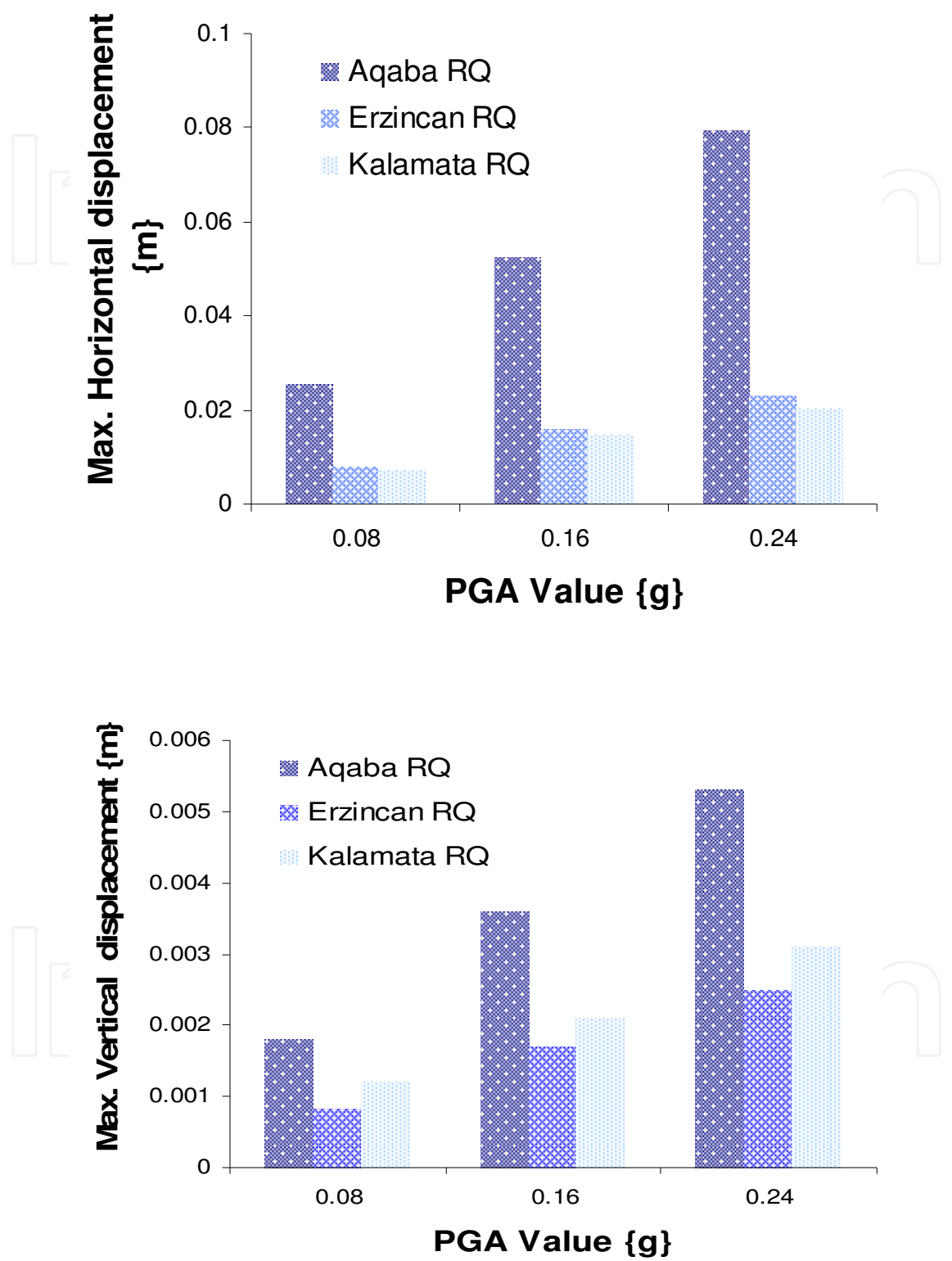


Fig. 12. (a) Maximum horizontal displacements, (b) Maximum vertical displacements on the top of Catacombs, for Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA.



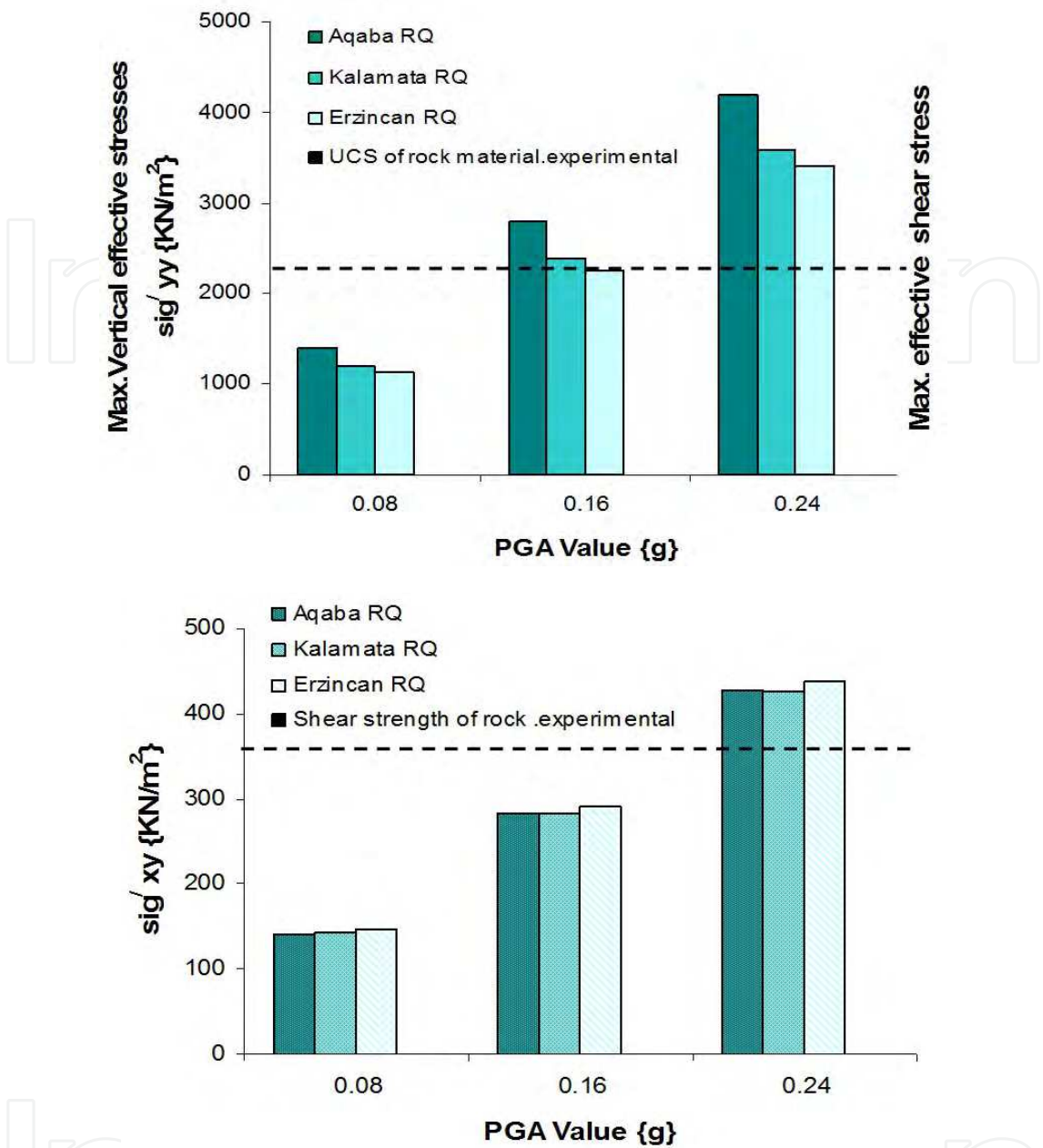


Fig. 13. (a) Maximum vertical effective compressive stresses  $\sigma'_{yy}$ , (b) Maximum effective shear stresses  $\sigma'_{xy}$  on the base of rock pier\_1, for Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA.

### 6. Polymer anti-seismic piling to protect the catacombs against strong earthquakes

We employed a newly developed polymer seismic isolation method, which has been employed successfully to retrofitting the Nakagawa underground station in Yokohama city (Japan), to protect the underground structures of catacombs of Kom El-Shoqafa against strong earthquakes with  $PGA > 0.24g$ . The polymer seismic isolation method outlined in Figure 14 presents certain advantages compared to other conventional anti-seismic methods (such as the steel jacket method). This method is apriority suitable for the seismic protection

of the underground monuments, because the application of this technique is non-destructive and do not involve any change in the original materials of the monuments; in addition we do not employ new materials or constructions to the monumental initial structure.

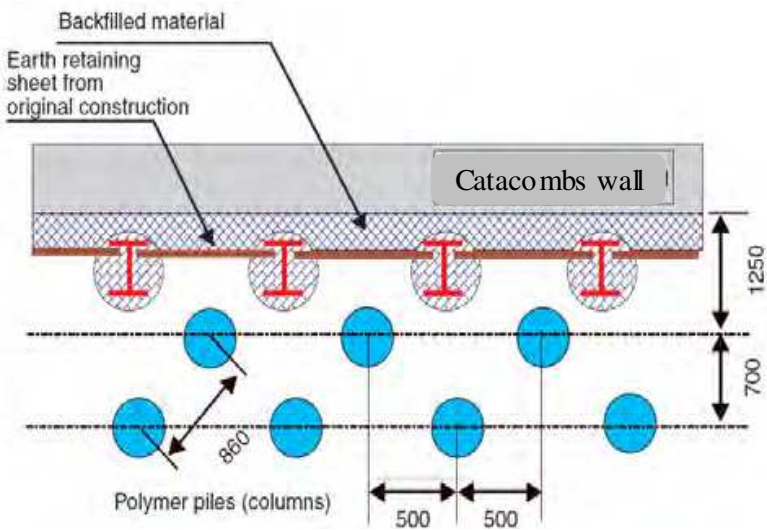
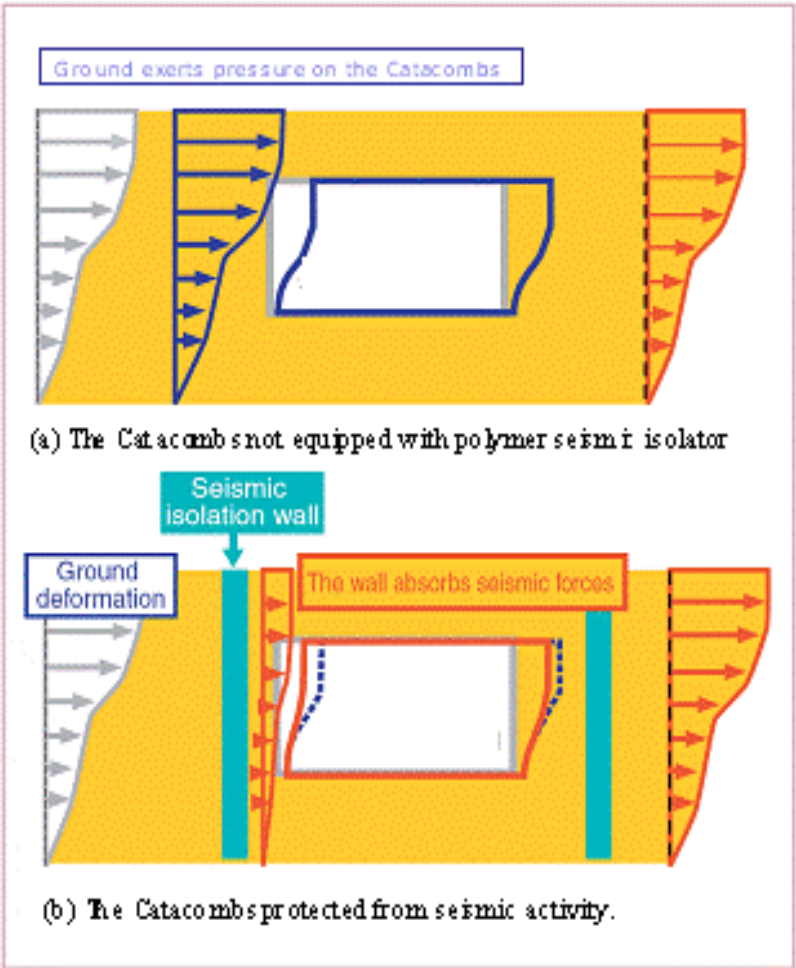
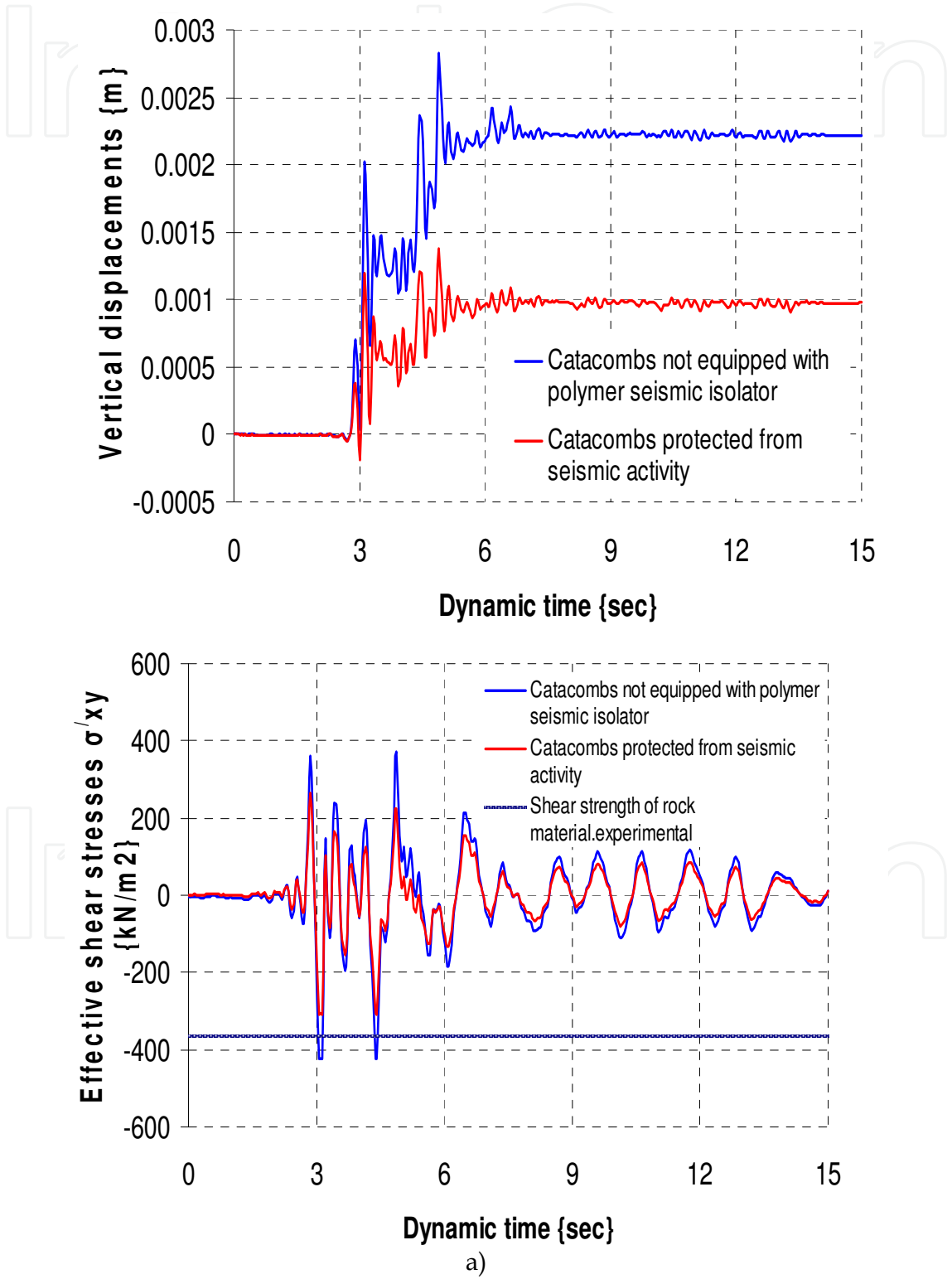
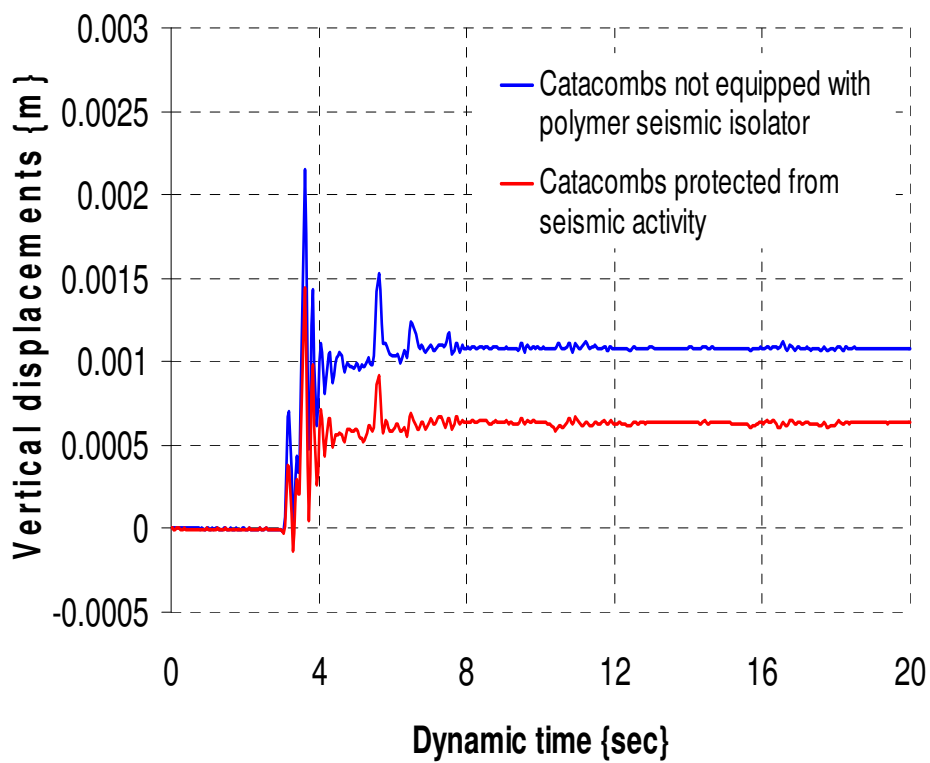
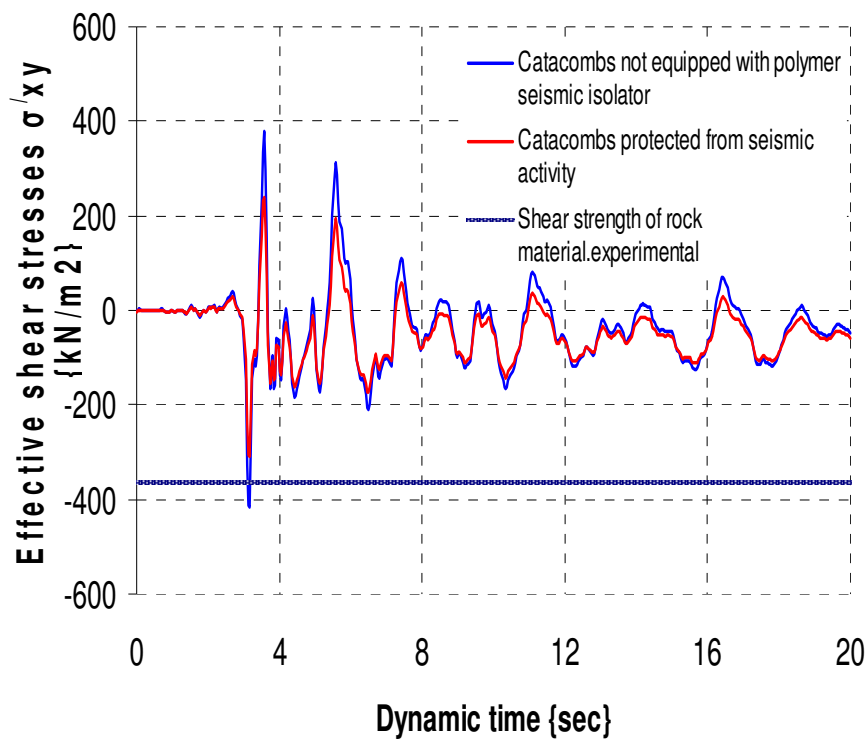


Fig. 14. The polymer seismic isolation method to protect the catacombs against strong earthquakes, (conceptual diagram).

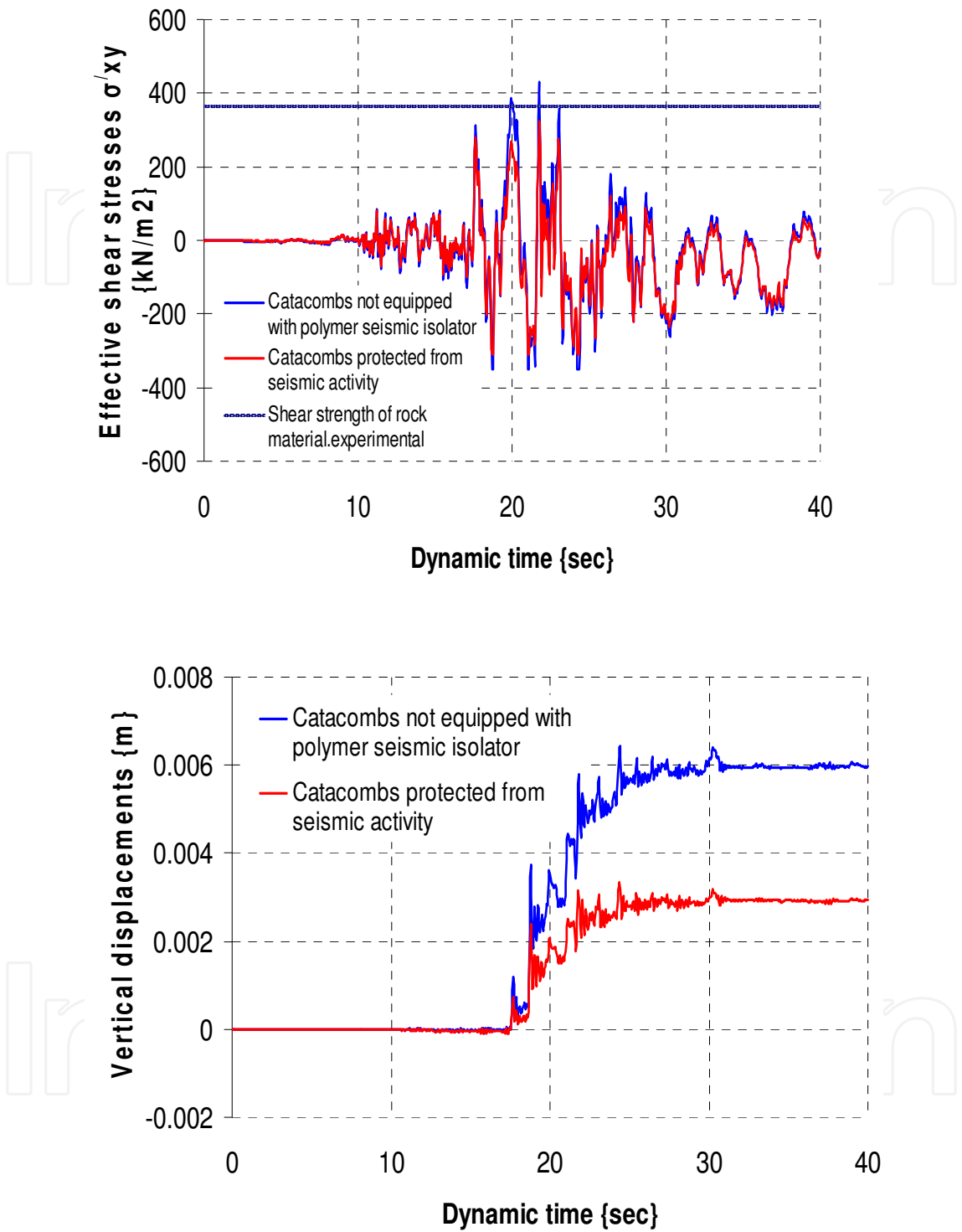
The polymer seismic isolation method' involves the construction of polymer walls on both sides of underground structure in order to reduce the seismic actions transmitted from the surrounding ground to the structure. The stiffness of the polymer material should be about 1/10 to 1/100 that of the surrounding ground. This method is not intended to prevent or control the seismic ground deformation itself, but to isolate structures from seismic forces transmitted from the surrounding ground (Hemeda, 2008).





b)





c)

Fig. 15. Vertical displacements, Effective shear stresses  $\sigma_{xy}$  - time histories on the base of rock pier 1 before and after the installation of polymer anti-seismic slurry walls. (Figure 9 at the right side of rotunda). (a) Kalamata (b) Erzincan (c) Aqaba earthquakes. PGA = 0.24g.

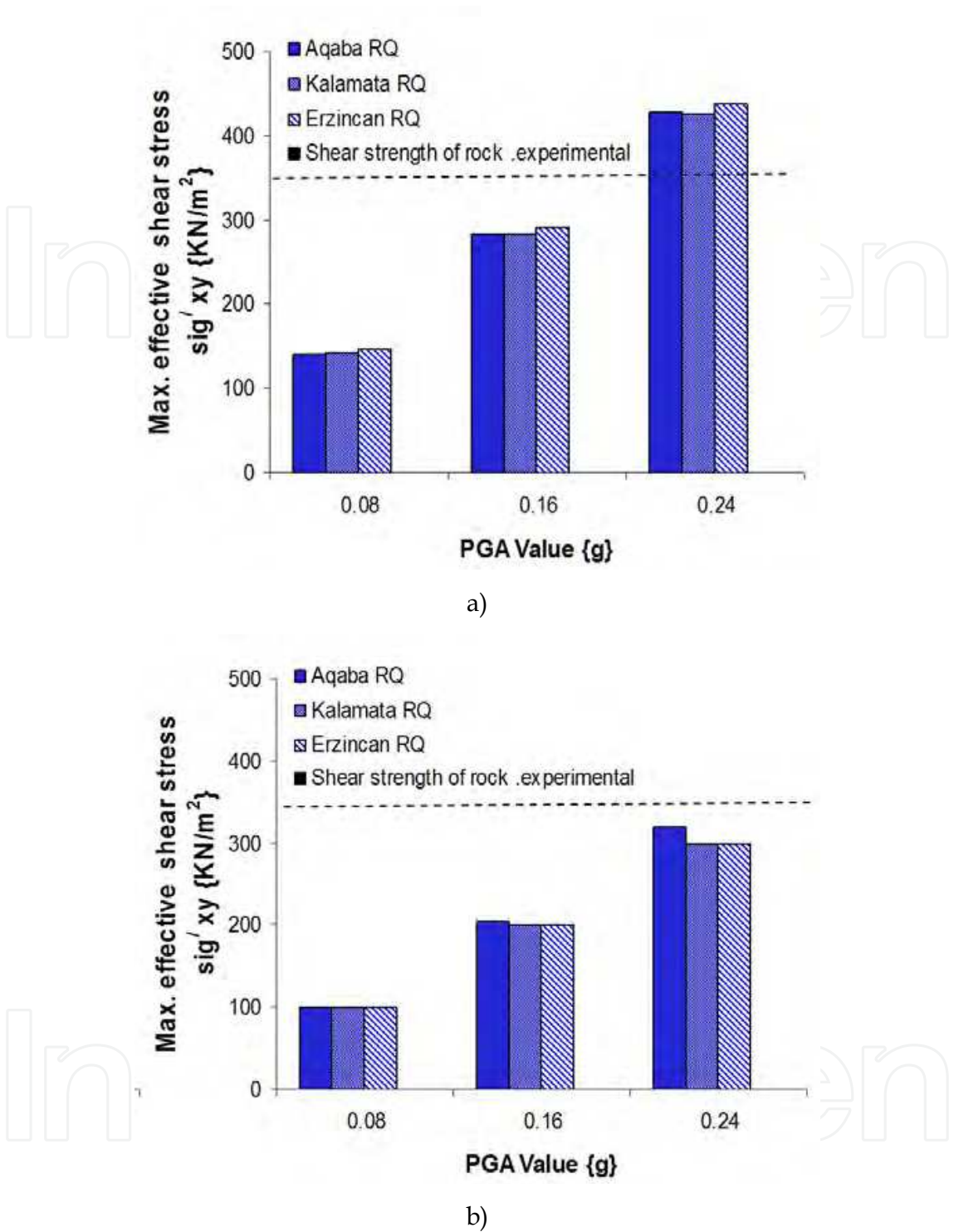


Fig. 16. Maximum effective shear stresses  $\sigma'_{xy}$  on the base of rock pier\_1, (a) Initial model (b) After the installation of polymer anti-seismic piling. For Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA.

With the installation of polymer anti-seismic slurry walls, the shear forces on the rock pillars, which are the most vulnerable parts inside the catacombs, reduce by up to 50% for the three earthquakes scenarios, (see Figure 15). The effective shear stresses on the pillars are also reduced considerably: in particular from 410  $\text{kN/m}^2$  to 250  $\text{kN/m}^2$  in the case of

Kalamata earthquake for  $PGA = 0.24g$ , from  $400 \text{ kN/m}^2$  to  $280 \text{ kN/m}^2$  in the case of Erzincan earthquake, and from  $430 \text{ kN/m}^2$  to  $300 \text{ kN/m}^2$  in the cases of Aqaba earthquake. The decrease of the computed acceleration values was also obvious in all the three earthquakes scenarios; for example the horizontal acceleration on the top of the catacombs decreases from  $3 \text{ m/s}^2$  to  $2 \text{ m/s}^2$  in the case of Aqaba earthquake and from  $2.6 \text{ m/s}^2$  to  $2.3 \text{ m/s}^2$  in the case of Erzincan earthquake. The horizontal displacements on the top of catacombs decrease from  $24 \text{ mm}$  to  $20 \text{ mm}$  in the case of Kalamata earthquake and from  $25 \text{ mm}$  to  $21 \text{ mm}$  in the case of Erzincan earthquake, while in the case of Aqaba earthquake, for  $PGA = 0.24g$ , the displacement reduction is lower; from  $80 \text{ mm}$  to  $78 \text{ mm}$ . The vertical displacements at the top of catacombs decrease from  $2.8 \text{ mm}$  to  $1.0 \text{ mm}$  in the case of Kalamata earthquake, from  $2.4 \text{ mm}$  to  $1.5 \text{ mm}$  in the case of Erzincan earthquake, and from  $6 \text{ mm}$  to  $2.5 \text{ mm}$  in the case of Aqaba earthquake.

From the above short presentation and discussion it is obvious, that the seismic stability of the catacombs has been upgraded after the installation of the polymer anti-seismic slurry walls in the perimeter of an underground monument. The relative deformations are reduced considerably and the developed seismic shear forces on the sidewalls can be easily controlled within acceptable safety margins even for major earthquakes.

It is expected that the above-mentioned polymer seismic isolation method may contribute effectively to the improvement of the seismic safety margin of underground monuments, without employing other retrofitting techniques, which may modify the architectural and archeological principles of the preserved monuments.

## 7. Conclusions

Considering all other affecting factors (aging, weathering, multiple geotechnical and seismic instability problems and the specific geometry of the complex it has been shown that the low rock strength affects seriously the safety of the catacombs both under static and seismic loading conditions.

The results from the 2D-3D static analysis indicate that the ground displacements above the catacombs are small (the maximum total vertical displacements are of the order of  $2.6 \text{ mm}$  to  $3 \text{ mm}$  in the whole domain, and the peak horizontal displacement is  $1.0 \text{ mm}$ ). Some rock piers exhibit relatively high compression stresses. The calculated peak effective principal vertical compressive stress on the pillar 1 is  $-1.74 \times 10^3 \text{ KN/m}^2$ . The calculated peak effective principal tensile stress is  $200 \text{ KN/m}^2$  and the factor of safety of the rock pillar 1 is  $1.47$ , which is not adequate, where the acceptable safety factor must be  $> 1.6$ . Also the overstress state is beyond the elastic limit. It is so then damage does occur. You can read more on damage assessment and future work that can be done using damage indices (journal of structural engineering 137(3): 456-567: damage-based design earthquake loads for sdof inelastic structures).

The seismic analysis of these underground monumental structures for three seismic scenarios of different  $PGA$  values, proved that for  $PGA > 0.10g$ , which is a rather low value considering the seismic activity and the past seismic history of the city, there are some critical supporting parts of these catacombs structures (i.e. rock piers and columns) that are not safe, and in general, the catacombs need considerable strengthening.

We also presented some preliminary results applying a polymer seismic isolation method which has been proved to contribute effectively in reducing the induced inertial forces on this type of underground monuments.

## 8. Acknowledgment

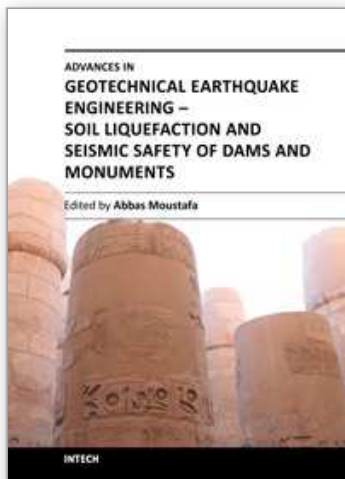
The author wish to express his deep acknowledgement to Professor Ptilakis.K, Dr Bakasis. I, Civil Engineering Department, AUTH, Greece for his support in performing part of the experimental and numerical analysis.

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## **Advances in Geotechnical Earthquake Engineering - Soil Liquefaction and Seismic Safety of Dams and Monuments**

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